Science: Philosophy, History and Education

William F. McComas *Editor*

Nature of Science in Science Instruction

Rationales and Strategies

Springer

Science: Philosophy, History and Education

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ISSN 2520-8594 ISSN 2520-8608 (electronic)
Science: Philosophy, History and Education
ISBN 978-3-030-57238-9 ISBN 978-3-030-57239-6 (eBook)
https://doi.org/10.1007/978-3-030-57239-6

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This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Foreword

It was more than 20 years ago that the book *The Nature of Science in Science Education: Rationales and Strategies,* edited by William McComas, was published. This has been one of the most widely read books about the nature of science (NOS) ever published. Therefore a few years ago I proposed that it was time for us to have a new, updated, and revised edition. Bill agreed and started immediately working on the book. Eventually, the outcome is not the 20th anniversary edition I envisioned; it is a new book with a targeted focus on teaching NOS, including updates from several of the initial key contributors and a large and varied number of new ones. Now we find 39 chapters, contributed by 68 authors across the spectrum of contemporary discussions on what NOS is and what and how we should teach about it. This is a landmark book that will be very useful to science educators and teachers alike. An important feature is that it is primarily a book for practitioners, those tasked with teaching aspects of NOS effectively. However, its academic quality is high; the editor has made no compromise in that respect.

I have a personal story to share that highlights the usefulness of the present book. I started working as a science teacher in 2001 without having undertaken a preservice science teacher course (such courses were not, and still are not, compulsory in Greece). When I started working, having a degree in biology and a master's in genetics, I did not even know that there was research in science education. Nevertheless, I was lucky enough to be hired at Geitonas School, where there was an active Department of Science Education. One of the science coordinators there, Alexandros Apostolou, gave me the 1998 *Nature of Science in Science Education* and suggested that I read it. Indeed, I did, and I suddenly realized how much our students were missing without NOS in the curriculum. Eventually, we developed a NOS course that was very successful, both in terms of impacting students' attitudes and their understanding. But what was more significant for me was the realization of how much history and philosophy of science have to contribute to science education. I am glad that several years later I am the editor of a book series and a major journal that focus on exactly that.

Perhaps the most influential chapter that I read was the one written by Bill himself (and significantly updated in this new volume) about the principal elements of NOS and about dispelling the respective myths. I still remember how much that I already knew started to come together and become meaningful while reading that chapter. Myths abound in science education, and this is one reason that NOS has to become a central curricular goal. What is more important, notwithstanding the discussions about what we ought to teach about NOS, is that while teaching I came to realize that students had a number of strongly held preconceptions about what science is and how it is done. Therefore, I have long argued that the teaching of NOS should not begin by any normative standards, but rather by aiming to address students' preconceptions and to dispel the related myths: that there is a single scientific method, that science is done by lonely geniuses, that scientific knowledge ought to be certain, and more. The teaching of NOS should initially aim at a process of conceptual change. Then, of course, this understanding should become more sophisticated. Suggestions abound about how to achieve this in the present book.

Therefore, I am delighted to present this new book, which I believe will become a landmark just like its predecessor. Bill McComas should be commended for bringing together almost all scholars who have published on NOS during the last quarter century while introducing many new voices and generally for delivering a book that will become both an inspiration and useful tool for science teachers and science teacher educators.

Geneva, Switzerland

Kostas Kampourakis
Series Editor

Preface

Images of the nature of science (NOS) vary widely. The translation of NOS to the K-16 science education curriculum has been a long-standing goal and a central pillar of the recent Standards Movement, in the USA and elsewhere. The NOS images recommended for inclusion in science education range along a continuum that runs from broad domain-general features of scientific practices and values at one end to narrower domain-specific "science-in-the-making" depictions of building knowledge at the other extreme. Over the decades of the twentieth century, scholars have taken various stances (e.g., epistemological, ontological, historical, pedagogical, feminist, psychological, sociological, and economical) to represent how scientific knowledge is established and changes and how best to communicate about science as a way of knowing. While writing this preface, the New Horizons satellite has beamed back images at the edge of our solar system from a distance that takes 6 hours to reach Earth traveling at the speed of light. The Mars rover "Opportunity" has completed a 15-year mission as a robotic geologist. A lunar vehicle successfully landed on the dark side of the Moon with a satellite positioned to stream back, for the first time, dark side live surface images. All are examples of STEM disciplines working in integrated ways to build knowledge. We have learned how to learn. Artificial intelligence (AI) is being increasingly deployed in our lives to monitor and intervene in social, educational, and political decision making. We are learning how to learn about learning.

Over the past century there have been complex developments regarding the philosophical and historical characterizations about NOS and the pedagogical frameworks for teaching NOS.

But when did teaching about NOS become a goal for science education? How did images about the NOS become a targeted curriculum topic and a learning goal for K-16 science education? From a US perspective, the decade of interest is the 1950s. In that decade, post-war developments in the sciences, mathematics, and engineering shifted from industry efforts alone (e.g., General Electric, Westinghouse) to broader federal agendas with the formation of the National Science Foundation. Then, as now, the focus is on developing new knowledge for a competitive workforce to steer our science-and-technology-driven economies, e.g., agriculture, health and medicine, telecommunications, artificial intelligence, and energy, among others.

The catalyst for rapidly changing the face of K-12 science education in the 1950s was the US reaction to the launching of the USSR satellite Sputnik. Within a single decade, 1955 to 1965, hundreds of millions of dollars were invested in the development of curriculum and facilities, employing a top-down process from high schools first followed by middle and elementary grades. Once the curricula were established, NSF funding was directed to teacher institutes to prepare staff to teach these new inquiry-based science programs. Scholarly writings on this period of science education can be found in John Rudolph's *Scientists in the Classroom* and George DeBoer's *A History of Ideas in Science Education.*

In post-secondary education the catalyst was Harvard University and then President James Bryant Conant's development of the *Harvard Case Studies in History of Science* course project. The course was designed for returning WWII GIs enrolling in non-science degree programs. The goal was to prepare the veterans for leadership roles in the rapidly emerging new science-and-technology-based industries. The adopted strategy was to use "historical case studies" to introduce and nurture rich understandings of the "tactics and strategies" employed in developing scientific knowledge. Criteria for selecting the cases included illustrating one or more of the *tactics and strategies of science*:

- Revealing the evolution of new conceptual schemes as a result of experimentation
- Detailing advances in science, e.g., the progress taking place
- Making distinctions between advances in mechanical contrivances (tools) or primitive chemical process (metallurgy or soapmaking) and advances in science (discovery of oxygen, cell theory)
- Revealing the symbiotic nature of industry and science (agriculture, medicine, electricity, and telecommunications)

Leo Klopfer adapted the *case studies* program for use in high school programs: *History of Science Cases* or *HOSC*. William Cooley and Leo developed the first NOS instrument "Test on Understanding Science" or TOUS to assess the impact of HOSC on learning. The 60-item TOUS focused on three themes:

Understanding about scientists – e.g., generalizations about scientists as people, institutional pressures on scientists, and abilities needed by scientists

Understanding about scientific enterprise – e.g., communication among scientists, scientific societies, instruments, international character of science, and interaction of science and society

Understanding about methods and aims of science – e.g., theories and models, controversies in science, science and technology, generalities about scientific method, and unity and interdependence of the sciences

From the 1950s to 1990s developments taking place in the learning sciences and within science studies academic communities – history, philosophy, sociology, anthropologies, and economics of science – ignited our understandings of how we have learned how to learn about nature. But this scientific interrogation of nature has also ignited our understandings of how to learn about learning and the design of learning environments as well. John Rudolph's new book *How We Teach Science: How It's Changed and Why It Matters,* Harvard Education Press, scrutinizes the various efforts, policies, and products that constitute the emergence of science education through the lens of teaching the scientific method. What he presents is much more than a descriptive narrative of events, institutions, and people involved in science education. Rudolph has crafted an engaging tapestry of how political, economic, pedagogical, psychological, philosophical, and technological forces have all influenced and been influenced by matters of science causing the focus of science education to swing back and forth between teaching science knowledge and teaching scientific methods, processes, and practices.

The parade of science over the last 300 years has been dynamic, to say the least. New tools, technologies, and theories have shaped science pathways first in physics and chemistry for the early paradigmatic sciences; in population biology through Darwinian evolution and the Great Synthesis and on to molecular biology and medical sciences; in quantum mechanics; in materials, communication, and information sciences; in geosciences and Earth systems sciences; and in neurosciences and brain sciences, to name but a few. Advancements in science over the centuries have spawned multiple philosophical perspectives to account for the thinking and growth of knowledge therein. Over the last 100 years there were three major periods in philosophy of science:

1. The experiment-based hypothesis testing view that gave us logical positivism, logical empiricism, and deductive-nomological explanations to account for the justification of scientific knowledge claims
2. The history-based view of theory development and conceptual change that gave us paradigms, research programs, heuristic principles, scientific thema, and research traditions to account for the rational growth of scientific knowledge
3. The model-based view of cognitive and social dynamics among communities of scholars that gave us social epistemology, naturalized philosophy of science, and accompanying epistemologies to account for the deepening and broadening of scientific explanations

In his book, *The Structure of Scientific Revolutions*, Thomas Kuhn postulates that the characteristic feature of scientific revolutions is a period when fundamental beliefs clash with competing ideas when paradigmatic shifts are being contemplated by communities of scientists. Kuhn refers to this period as moving into "Crisis"; others imposed the term Chaos. During Crisis period, different competing theories and models vie to explain the established knowledge claims while also reconciling the mounting number of anomalies generated by the old paradigms. Periods of reconstructing group commitments, with all the competing perspectives, are seen by Kuhn as a necessary dynamic for the growth of scientific knowledge and the maintenance of scientific communities.

Examining the diversity of thinking about NOS presented in this volume, it is clear that the NOS community of scholars is presently in a period of reconsidering group commitments, Kuhnian Chaos or Crisis. The contributions to the volume represent a broad diversity of stances about how to infuse NOS into educational experiences and the design of curriculum, instruction, and assessment models. Some authors view NOS and inquiry as being congruent; other authors see them as being disparate separate entities. Some prioritize the learning of domain-general viable consensus view framework features of NOS. There are stances for attaining "introduction to science instruction" level understandings and other stances for deep-seated "problematizing the evidence" for science decision making. Others embrace the domain-specific dynamics of knowledge building, but critics state that it is doing philosophy and is not an introduction to science. Others maintain that epistemic reasoning via problematizing and interrogating how evidence is obtained, constrained, and used is the essential practice for "doing science." There are differences regarding the formats – lesson-driven vs. unit-driven designs – for teaching NOS, with deploying whole science historical approaches vs. vignette or questioning approaches to infuse history of science, and there are contrasting perspectives regarding what we mean by students' explicit engagements with NOS. Perhaps most pernicious though is the lack of agreement with how to measure NOS understandings. Since the development of TOUS by Cooley and Klopfer, there have been numerous instruments designed to measure "knowledge and views about science." But these various measurements are, not surprisingly, strongly aligned with the science studies perspectives, mentioned above, or influenced by views of science held by the NOS scholars, e.g., empiricism, logical positivism, realist, instrumentalist, semantic, pre-/post-Kuhnian, model-based, naturalized, strong program, actor network theory, etc. Indeed, ["t]he nature of science is a fertile hybrid arena" (McComas et al. 1998, p. 4)

Fusing together the prior volume's chapters into the current volume has made more apparent the essences of this "Chaos/Crisis" during this 20-year period. As you will note, this volume does take some stands on NOS teaching and learning issues, even as we understand that science and its portrayals are dynamic endeavors as detailed in each of the four sections:

Section I – Background Knowledge for Inclusion of NOS in Science Teaching Settings
Section II – Background on Teaching the Nature of Science
Section III – Generalized NOS Instructional Strategies
Section IV – NOS Instruction in Specific Settings

How do we respond? Handling anomalies is at the heart of doing science. Building, polishing, and refining our theories and models is the name of the game. Consider our 150 years of developing the theory of evolution, first at the macro-organismic level, next at the cellular genetic level, and now at the molecular level. What are the salient modifications and anomalies in NOS to guide us during reconstruction? What are our goals? Is there agreement on them? Is their agreement upon evidence? Or are we embroiled and steeped in incommensurability battles?

Given the fact that NOS in K-16 is influenced by philosophical, social, political, psychological, and practical realities, how should readers view the various chapters? What should they consider in answering the question – how and what should be the concrete and practical recommendation for including NOS in K-16 programs? What are the methods, procedures, and pathways needed to achieve those goals and bring the NOS community together? What more do we need to know and do? Might there be a duality solution akin to particle and wave theories of light?

As we have learned how to learn about learning, there has been a progression to identifying more nuanced forms of knowledge which have led to new theories of learning and new learning goals. In the *Programme for International Student Assessment* (PISA) Framework and the *USA Framework for K-12 Science Education,* learning goals are parsed out into conceptual, procedural, and epistemic categories. The recent Organisation for Economic Co-operation and Development (OECD) policy report *The Future of Education and Skills 2030* Project proposes a tripartite "learning framework" that parses competencies into:

- *Knowledge* as disciplinary, interdisciplinary, epistemic, and procedural
- *Skills* as cognitive and metacognitive, social and emotional, and physical and practical
- *Attitudes and values* as personal, local, societal, and global

We might ask how well our NOS models fit with these competencies. We might also ask how our graduating students will achieve the appropriate level of expertise for the 2030 OECD yet-to-be-defined targets for literacy, numeracy, data literacy, health literacy, and digital literacy. I'm wondering then what should we decide are the guiding criteria for selecting cases that depict the tactics and strategies and learning goals of science for the twenty-first-century citizens of the world. Determining such criteria and cases, with guidance from the perspectives in *Nature of Science in Science Instruction: Rationales and Strategies,* is a good place to start these conversations.

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Acknowledgments

It has been a sincere joy to be part of a multi-year, international collaborative project targeting a central question, how to teach aspects of nature of science (NOS). The intellectual contributions offered here come from an accomplished, diverse, and experienced group of scholars, all of whom agree that nature of science is the foundation of high-quality science instruction.

This book may be the most recent contribution in support of NOS instruction, but we stand on the shoulders of many who have long been involved in the history-philosophy-sociology of science communities and have given us increasingly rich descriptions of how science functions as a discipline. In turn, even though advocacy for NOS instruction can be found in the science education literature for more than a century, we recognize the pioneering efforts of science educators such as James Robinson and Michael Martin who were among the first to specify a clear role for NOS in science instruction in the mid-1960s. The last 50 years has been a particularly rich time for NOS research with many contributions from many including interest from colleagues who represent a range of nations, contexts, and scholarly perspectives.

I also want to acknowledge the *International History, Philosophy, and Science Teaching Group* (IHPST) and its journal *Science & Education*. This organization with its regular conferences and well-regarded journal is a major forum for conversations about the intersection of the social studies of science and science education. That has done more than any individual to move the field forward. It has been my pleasure to have been a member almost from the start having attended most of the meetings in the past quarter century. I look to this group for inspiration and encouragement and have been pleased to feel welcomed by the worldwide members of IHPST.

I offer sincere thanks to the more than 60 authors whose work fills these pages and stands to enlightens us all. For many this has been an odyssey of cycles of revision working together to try to create the most useful book possible while reducing the inevitable overlap that came when almost everyone initially felt a need to describe the nature of science and defend why we need it. One colleague said

recently, “I have never worked with a more hands-on editor,” and while I am not positive, I would like to see this statement as a compliment. What I do know is that many of the authors contributed far more than their own chapters with their work in providing extensive internal peer review that has, we hope, resulted in a useful and internally consistent book.

There is one group of authors featured in the book you now hold who are due special accolades. Here I refer to Fouad Abd-El-Khalick, David Broersma, Michael Clough, William Cobern, Cathleen Loving, Norman Lederman, and Michael Matthews, all of whom contributed to *The Nature of Science in Science Education*, a book with a similar purpose to this one, more than 20 years ago. Yet they came back for more! When I realized that I would be joined – again – by this core group of individuals, I knew our project would be a success.

Of this group, no one deserves my sincere thanks more than long-time friend Mike Clough. Feel free to ask him about our first meeting a quarter century ago, but as he likes to tell the story, it may not have been auspicious! Yet, here we are still working together to improve science teaching and learning through NOS. The important contributions that Mike has made to NOS studies through his research and advocacy are found throughout this book as cited by others but resonate clearly in the chapters that he and I have written, rewritten, edited, and negotiated together for months. These opening chapters would not be as powerful without his intellectual contributions.

I am also deeply appreciative of individuals who have made their own outstanding contributions to NOS studies and have been particularly helpful to me through the years. These include Richard Duschl, who wrote the preface to this book, and Kostas Kampourakis, who provided the foreword to the series. Rick and Kostas have been more helpful than they may know through their countless conversations with me and their individual contributions to NOS education. Another long-time colleague who deserves special thanks is Michael Matthews, arguably one of the most important voices in this field. He is the founder of IHPST and constant supporter of all those who care about NOS and HPS and their impact on science teaching.

Let me conclude by mentioning to two vital supporters of this project. One is Jennifer Oramous, graduate student extraordinaire, and the other is former student Noushin Nouri (now Professor Nouri). For several years Jenn has assisted me and the authors at every turn, looking up references, tackling submission challenges with the online system, gently reminding authors of deadlines, and so much more. This project has been much more pleasurable because of Jenn’s assistance and support and the final product has her mark throughout. There is no way I can adequately thank her. Noushin, one of the co-authors of Chap. 4, and, was incredibly helpful throughout. In addition to her assistance with this key chapters, her grasp of the literature has added much nuance and depth to this project. I am pleased to report that both Jenn and Noushin are poised to make their own contributions to science teaching and learning.

Thanks to everyone involved in this project including Michelle Finney of Finney Creative for producing some wonderful graphics that now grace pages in this book, graduate students who proofread draft chapters, and particularly the colleagues who so helpfully critiqued my account of the nine key NOS elements.

Finally, I would like to extend my appreciation to the Springer team – principally Claudia Acuna, Anitta Camilya and Enayathullah – who have guided the development of this book through its long gestation and have remained such good partners throughout.

Now it is up to the science education community to put these ideas into action and use NOS to enliven, inform, energize, and enhance science instruction. Many of us have long viewed NOS as a necessary foundation aspect of science instruction, but it is now time to make that assertion a reality wherever and whenever science is taught.

William F. McComas

Introduction

This introduction is designed to introduce readers to the rationale and content of the book while providing an overall view of its organization. First though, let us remind ourselves that all of us involved in this project accept the proposition that all students have an introduction to NOS as their foundation as science learners and as an element of science literacy that all citizens should possess. We have seen increasing attacks on science with dismissals of its conclusions as if they were little more than matters of opinion. This is dangerous; students must appreciate and apply the rules of the game of science in making value judgments about the products of the scientific process that surround us and dismiss faulty claims that only seem to be grounded in science.

The set of chapters found at the beginning are designed to establish what is the nature of science (NOS) and what is its scope from a content perspective, but even before encountering what is found there, we might profit from stepping back and looking briefly at the notion of knowledge that has generally defined the science curriculum for much of its history. Knowledge comes in a variety of forms with nuances as many as there are scholars thinking about such issues, but basically there is declarative knowledge, procedural knowledge, and epistemic knowledge (Pritchard 2018).

Declarative (sometimes called conceptual) knowledge targets knowing in general. As an example, consider that "He" is the chemical symbol for helium, one of the noble or inert gases, a fact that all chemistry students should know. Procedural (or imperative) knowledge relates to the ability to perform a task like balancing a chemical reaction. Of course, it is possible to balance a chemical reaction using algorithmic tools without really understanding why one follows those steps, so we should note that procedural knowing is not one thing but has both superficial and much deeper states. The science curriculum, unfortunately, focuses primarily on declarative knowledge and somewhat superficial procedural knowledge. How often do we ask why it is important for children to know the names of the planets in order? How frequently do we assess procedural knowledge in ways that reveal its depth? We frequently provide students instruction on how to use the microscope properly even as we fail to give them opportunities to apply that knowledge in pursuit of personally interesting and/or relevant problems. However, despite suggestions for how we might share declarative and procedural knowledge more effectively and engagingly, we do a reasonably good job introducing science learners to these sorts of knowledge. We might call the knowledge of cells, planets, chemical elements, and Newton's laws as traditional or typical science content.

Epistemic knowledge is another domain entirely. Here we find information about how knowledge is created by asking questions like "What even exists?" (an ontological question), "How do things happen?," and "How do we know?" Of course, such questions are discipline specific (Knorr Cetina 1999). This book does not presume to answer such questions about science even though science teachers and learners are the hoped-for beneficiaries of the content of this book. Rather, this book works to define a domain of epistemic knowledge that we recommend should also inform the science curriculum just as traditional science content has done for centuries. This domain, the epistemology of science, is often known as nature of science primarily by those in the science education community. We do not presume to have made original contributions to understanding how science functions but have examined the conclusions of experts in the history, philosophy, and sociology of science and others and here offer recommendations for what conclusions from their work would best inform the science curriculum.

This process of working with a knowledge base provided by others to craft recommendations for the content of introductory science programs at all levels is what science educators do. I say this not defensively, but definitively. Researchers in biology, chemistry, and physics help to define the knowledge base of their disciplines and ideally work with science educators to make decisions about how findings in those areas are communicated in school setting. We welcome that same collaboration in our quest to have students leave the school science experience with a firm understanding of the shared tools of science and knowledge of the focus and limitations of science and generally appreciate and be able to apply knowledge about "how science works."

A third of a century ago, Richard Duschl authored a landmark article titled *Science Education and Philosophy of Science: Twenty-Five Years of Mutually Exclusive Development* in which, as the title implies, he offered the concern that the epistemic knowledge of science had not yet been made part of the science curriculum. In the intervening years many have made contributions to the field of NOS, and there is widespread understanding that NOS-related knowledge must be part of plans for science teaching and learning. However, as we have seen recently in the USA, even the current science teaching standards, the *Next Generation Science Standards* (NGSS 2013), give only cursory prominence to NOS, but at least recommendations are included. We now need to get teachers, textbook authors, and assessment experts to pay attention. Focus on the inclusion of NOS-related standards has ebbed and flowed through the years, but perhaps because of my inherent optimism, it feels as if NOS is finally now a permanent part of the science curriculum conversation. This book is positioned and even designed to move the conversation from "why NOS?" to "what NOS?" to the most important question of all "where and how do we teach NOS?" The robust recommendations contributed by the many authors that grace its pages are a response to this last rhetorical question.

More than 20 years ago, I and some of the scholars whose thoughts appear in the pages of this volume tackled the first two questions while providing some strategies to address the third. That book was *The Nature of Science in Science Education: Rationales and Strategies* (McComas 1998). With the passing of a score of years, it seemed reasonable to update that earlier work with a second edition. However, as work proceeded, it was obvious that we maintained only a relative handful of words and thoughts from that original book as it really was time for something new. So, we are pleased now to offer *Nature of Science in Science Instruction: Rationales and Strategies*. This title was not chosen to be so similar as to be confusing, but it is offered with recognition that the key issue now is to focus our energies on assisting teachers and other key stakeholders to include elements of NOS across all levels of science instruction. Also, please note another more subtle but important change. The title now no longer contains a definite article "the" removed in favor of a more open and potentially embracing view of this domain. None of us think that we have determined what "the" nature of science is, but we all agree that conversation about "nature of science" in schools is vital. With this in mind, we do hope to be forgiven if we occasionally slip back and forth between "the nature of science" and "nature of science." It is hard to give up old habits. Yes, I also realize that even the label "nature of science" is problematic; more is said about this in Chap. 1.

Organization of *Nature of Science in Science Instruction*

The book is founded on the understanding that we have reached a viable consensus for what aspects of NOS should be featured in science classrooms and offers a set of nine key NOS aspects or elements (sometimes called NOS sub-domains) clustered in three larger related spheres called the "Tools and Products of Science," "Human Dimensions of Science," and "Science and Its Limits." The call for proposals invited prospective authors to refer to this model set of NOS instructional goals and, as much as possible, provide strategies for teaching one or more of these goals to specific learners in specific settings. Thus, rather than a collection of NOS teaching ideas, the book has coherence centered on these themes.

In Part I, we find an introductory set of chapters that together provide an overview of nature of science as it pertains to teaching and learning based on an extensive review of the literature. We provide a discussion of the history or/and rationale for NOS in plans for science teaching. Here readers will find a detailed discussion of the nine recommended NOS aspects that are referenced throughout the book. This will be particularly useful for those new to the teaching of NOS. The part concludes with by synthesizing the research-based recommendation to guide effective NOS instruction.

In Part II, the authors provide more generalized background information to inform NOS learners. The authors here discuss the variety of research models available to scientists, a new conceptualization of investigative methodologies beyond the so-called stepwise scientific method. The final two chapters explore the challenges of observation in science and the distinction between science, technology, and engineering, a major issue with respect to the rising interest in STEM.

The remainder of the book provides both general and specific NOS instructional strategies. Part III offers many chapters related to NOS teaching strategies that may be generally applied. These include the use of metacognitive prompts, considerations of student thinking, or framing NOS as questions.

The final cluster of chapters in Part IV includes somewhat more specific instructional strategies. For instance, those linked to particular NOS elements (i.e., the limits of science), teaching NOS in particular ways (i.e., using history or science), or teaching NOS in specific environments (i.e., elementary settings).

I conclude by recognizing that not all of the authors likely fully agree with the set of nine key NOS elements. Indeed, they might not even support the way these notions are offered here as learning objectives, nor do they necessarily support every aspect of the definitions and descriptions of these nine. However, all authors are united in the view that NOS is vital and there is great profit in moving forward to assist all involved in science instruction to value NOS and develop ways to include it authentically, accurately, engagingly, and frequently throughout the science curriculum from science for the youngest students through the university years. Whether these plans find a home in teacher education programs, in school classrooms, or simply in the minds of interested individuals, we are confident that science education will be a richer discipline and our students will be more adequately prepared for their lives as citizens when afforded a fuller understanding of the nature of this thing called science. This last sentence came directly from the preface I wrote more than two decades ago yet still rings true today.

William F. McComas

References

Duschl, R. A. (1985). Science education and philosophy of science: Twenty-five years of mutually exclusive development. *School science and mathematics, 85*(7), 541–555.

Knorr-Cetina, K. (1999). *Epistemic culture: How the sciences makes knowledge*. Cambridge, MA: Harvard University Press.

McComas, W. F. (1988). *The nature of science in science education: Rationales and strategies*. Boston: Kluwer/Springer.

NGSS Lead States. (2013). *Next generation science standards: For states, by states*. Washington, DC: National Academies Press.

Pritchard, D. (2018). *What is this thing called knowledge?* (4th edn.). New York: Routledge

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Part I

Nature of Science in Science Teaching and Learning: Introduction

Chapter 1
Nature of Science in Science Instruction: Meaning, Advocacy, Rationales, and Recommendations

William F. McComas and Michael P. Clough

1.1 An Introduction to Science and Its Nature as the Foundation for Science Learning

For centuries, formal education has included some aspects of science content and process. The science curriculum has generally had a somewhat utilitarian focus with content related to what was necessary in specific trades, future education, the health and welfare of the individual or society, and general knowledge for citizenship. Some maintain that science is inherently interesting and, because of this, worthy. Regardless of why science has been included and often required in the school curriculum, the focus has traditionally been on covering vast amounts of content sometimes augmented with "hands-on" experiences. This aspect of the science experience has typically highlighted experimentation as a problem-solving tool accompanied by data collection that involves measuring, observing, and other processes of science. These important inquiry skills often are included in school science, and they provide fruitful opportunities for addressing the nature of science. However, NOS content has largely been neglected, and other aspects (such as the objectivity of scientists and the step-by-step scientific method) are frequently incorrectly or misleadingly offered as accurate lessons about how science works.

This general disregard for NOS is puzzling given that science has a pervasive, but often subtle, impact on virtually every aspect of modern life—both from the technology that flows from it and the philosophical and ethical implications arising

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_1

from its ideas. Science is increasingly being ignored by policy-makers and the public, and thus citizens must come to understand how science works and even defend science from those who view well-established scientific consensus as mere opinion. Everyone ought to be well-educated regarding the most fundamental scientific knowledge but also understand science as "a way of knowing," more comprehensively, the NOS.

Before proceeding, what is meant by "science" and "nature of science" must be addressed. However, the complexity of science and its nature both defy simplistic and universally accepted definitions. While one very important outcome of NOS scholarship is that clearly demarcating science from other disciplines is problematic, an initial characterization of science is possible and needed to move forward.

1.1.1 What Is Science?

While no simple characterization can wholly capture what science is, a reasonable and brief definition is that science is a human endeavor directed at exploring the natural world to produce valid and reliable knowledge (explanations and generalizations) supported by evidence and reasoning that is, in principle, open to review by all. This definition is certainly too basic because existing knowledge and traditions constrain both the focus of the work of scientist and the tools (intellectual and otherwise) that can be brought to bear in the process of scientific work, but it is a good start. However, a more complete description of it can only be achieved through an examination of its nature and its products, our next section's topic.

Our modern term *science* comes from the Latin word *scientia* or *knowledge*. This was a generic use of the word in much the same way that *philosophy* was the label for a lover of knowledge itself. In this sense, many things could be called a science, and those seeking wisdom in any field were philosophers. However, thoughout much of history those working in ways that resemble our modern conceptualization of science were often known as "natural philosophers," and the domain was called "natural philosophy." The key here is that such individuals began slowly to limit their investigations to the natural world, increasingly valuing naturalistic explanations. Gradually, "natural philosophy" became "natural science" and finally just "science" as we call it today. This evolution was also seen with respect to the name for those working in the natural sciences. In 1833, polymath and historian of science William Whewell coined the term "scientist" (and "physicist" too for good measure) as a counterpoint to the common term "artist." The term grew slowly in popularity and finally emerged in the form that we know it today by the end of the nineteenth century. Scientific knowledge has become so vast that perhaps we have reached the point where calling someone a scientist requires greater clarity; even the description "biologist," "physicist," or "chemist" is quite broad, and only a label like biochemist, wildlife biologist, particle physicist, or vertebrate paleontologist or even more specific titles can truly capture the incredible level of specific knowledge and practice of those working in the natural sciences.

1.1.2 What Does the Expression "Nature of Science" Mean?

Nature of science (NOS) is not a description of how the natural world works (that's science itself), but rather a description of how the scientific enterprise works. Just as scientists devote their careers to better understanding the natural world, those interested in the nature of science want to understand how scientists work and engage with each other and society, how science answers questions, and how this thing called science generates knowledge about nature. The NOS addresses issues such as what is science, how science works (including issues of epistemology and ontology), how science impacts and is impacted by society, and what scientists are like in their professional and personal lives. Those interested in the study of science ask questions like "What, if anything, demarcates science from other human endeavors?", "In what sense are science ideas discovered or invented?", and "How is consensus regarding conclusions reached in the scientific community?"

In an earlier work (McComas et al. 1998, p. 4), we wrote and still maintain that:

> The nature of science is a fertile hybrid arena which blends aspects of various social studies of science including the history, sociology, and philosophy of science combined with research from the cognitive sciences such as psychology into a rich description of what science is, how it works, how scientists operate as a social group and how society itself both directs and reacts to scientific endeavors.

As a shorter characterization, "The nature of science involves the basic values and beliefs that make up the scientific world view, how scientists go about their work, and the general culture of the scientific enterprise" (AAAS 2001, p. 15). Although the term "nature of science" is occasionally used by some outside the domain of science education, this label has found a home and strong advocacy among those who care deeply about science teaching and learning. As stated in the preface, we agree that there is no single nature of science as might wrongly be inferred from "the" nature of science. However, as discussed throughout this book, much has been learned about the nature of science that science educators frequently recommend be shared with science learners in efforts to promote science literacy.

1.1.3 Why "NOS"?

For a variety of reasons, names other than "nature of science" have been suggested. These include Nature of Science Studies, Features of Science (Matthews 2012), History and Philosophy of Science, Ideas About Science (Osborne et al. 2003), Nature of Sciences, Nature of Scientific Understanding, Nature of Scientific Knowledge (Lederman 2007), Views of Science, and others. Of course, the specific name does convey a certain orientation, and the nuances represented by each of these suggestions has value. However, in the interest of space rather than because of a lack of interest, we have avoided an analysis of each. Rather, considering the long use of the "NOS" label in science education, we will continue that tradition throughout this book. Disagreements about the label "NOS" and referring to NOS instruction as "teaching NOS," "teaching about NOS," "teaching the NOS," reflect the perspectives and passions of those with interests in this pedagogical arena.

1.1.4 What About NOS Should Be Taught and Learned?

The ultimate set of NOS elements that should be the focus of science instruction and even how those elements are best provided in standards documents remains unsettled to some degree. This important debate will be highlighted and discussed in detail in Chap. 2, but a review here is important. On one side of the debate, we find that with a human endeavor as complex and diverse as science, some (Herron 1969) submit that no sound and precise description could exist concerning the nature and structure of science. Laudan et al. (1986) stated that "…we have no well-confirmed general picture of how science works, no theory of science worthy of general assent" (p.142). Decades ago Welch (1984) and Duschl (1994) also expressed concern about a lack of consensus regarding what image of scientific inquiry and growth of scientific knowledge should be shared with students. More recently, van Dijk (2011) has taken up the cause by suggesting that totally understanding science and therefore precisely demarcating it from other human pursuits is not possible. Even if this were true, this would not prevent us from adequately and accurately sharing a "big picture" view of science useful for school science purposes.

If we keep our focus on describing science for science learners—particularly in introductory instructional settings—there is much known about NOS that can and even must inform science education efforts directed at promoting science literacy. Convergence on a shared view of aspects of NOS worthy for inclusion in science classes has been developing for decades represented by suggestions in *Benchmarks for Science Literacy* (AAAS 1993), Osborne et al. (2003), McComas et al. 1998, McComas 2004), Lederman (2002), and the US Next Generation Science Standards (Achieve 2013). These sources offer similar but not identical sets of NOS content recommendations. Chapter 3 features an extensive discussion of nine key NOS ideas that many in the science education community see as a reasonable foundation for use in classroom conversations, standards, textbooks, and student assessment. This includes issues such as the distinction between law and theory, the place for creativity in science, the ranges of shared methods used by scientists, cultural and social elements that impact science, the role and nature of evidence, and other considerations in understanding the natural world.

These ideas frame NOS instruction in the US *Next Generation Science Standards*, although many in the science education community sought a much more prominent role for NOS in the document. Unfortunately, NOS appears almost as an afterthought in an appendix (Appendix H) with various NOS issues linked, often poorly, to the cross-cutting themes and science and engineering practices that along with science content are collectively called the three dimensions of science teaching. McComas and Nouri (2016) have suggested that NOS be featured as a fourth dimension of science learning. Nevertheless, NOS does appear in the document destined to inform and direct science teaching in US public schools in those states that adopt its recommendations. Furthermore, because NGSS has been so widely circulated generally both within and beyond the United States, its contents, including NOS, will likely impact thinking about science teaching broadly and for many years to come.

In establishing desired NOS learning outcomes, we agree with Matthews (1998) that we develop achievable objectives. He wisely states that, "It is unrealistic to expect students or prospective teachers to become competent historians, sociologists, or philosophers of science. …There is no need to overwhelm students with cutting edge [philosophical] questions." (pp. 168–169). Reflecting this, we strongly recommend striking a balance between a shallow and perhaps even banal description of how science functions and high-level discussions that would be much more appropriate in postsecondary history and philosophy of science coursework. While NOS must not be misrepresented or over simplified, students should be engaged in learning the fundamental and most meaningful ideas regarding the social studies of science with a goal to improve their science literacy for purposes of personal and societal decision-making. We further advocate that, while proposed NOS instructional goals should be debated and periodically reexamined, such discussions must not halt the teaching and learning of NOS in science education. Those who insist on the impossibility of defining NOS or recommend waiting until complete consensus is achieved can unintentionally set back efforts to ensure that all students leave school with NOS understanding sufficient for informed citizenship.

1.2 How We Know What We Know About How Science Works: A Brief Introduction

> *If you want to know about water, don't ask a fish*
> Chinese Proverb

Simply asking scientists about how they do their work is insufficient for understanding the scientific enterprise. Einstein (1934/1982) recommended that if you want to know how scientists work, "don't listen to their words, fix your attention on their deeds" (p. 270). Of course, scientists do understand the nature of their work better than most, but they are often so focused on understanding how nature works that they rarely stand back and deeply reflect on how science itself functions. That perspective is taken on by philosophers, historians, and sociologists of science along with psychologists who intently investigate those who do science and how they engage in their pursuits. Through these efforts, we have come to understand much about science and scientists. Science educators draw from this wealth of knowledge

Fig. 1.1 The four major disciplines that provide important evidence in support of an accurate picture of how science functions

to determine NOS content appropriate for inclusion in school science learning experiences and the preparation of those who will become science teachers.

Detailing the contributions of scholars who provide understanding about how science operates is beyond the scope of this book, but a cursory overview is necessary to appreciate the distinction between "science" and the "social studies of science." At a macro level, four major groups of experts have contributed to our knowledge of NOS (Fig. 1.1). Importantly, these scholars often have undergraduate and graduate degrees in science and may even have practiced science. Historians of science look to the past and often extract lessons about how science functions and how social systems and culture have impacted science. Philosophers of science often draw on evidence from history or logical analyses about how science works. Sociologists of science study the interactions of scientists as a social group and consequently develop insights about power structures, expertise, and how ideas come to be accepted within the community of scientists. Psychologists of science are not mentioned as prominently as the others in providing a vital nuance to any view of science. However, such scholarship has contributed significantly to our understanding of how all observation, including that by scientists, is impacted by pre-existing knowledge and presuppositions.

The combined contributions of experts in these areas have provided extensive descriptions about how science functions. Our job in science education is to consult the conclusions of these scholars who describe the enterprise of science and extract a rich, accurate, engaging, reasonably nuanced picture of the science to inform the science curriculum and teaching in ways that learners can understand, teachers can embrace and communicate, and instructional time will allow. The insights found at the intersection of the various social studies of science in Fig. 1.1 represent the content domain (NOS) which offers a rich view of science for those who have limited opportunity (i.e., school and informal science education settings) to take in the scenery.

1.3 A History of Advocacy for NOS in Science Instruction

Most science educators agree that NOS understanding is a crucial component of scientific literacy. Advocacy supporting students' understanding of science and its nature can be traced back to the early years of the twentieth century with antecedents extending back even further (Matthews 2012, 2015). Although the phrase "understanding the nature of science" has not alwasy been in use, some elements and characteristics of science were noted as goals worth pursuing in science teaching. For example, the Central Association of Science and Math Teachers (CASMT 1907) strongly emphasized inclusion of the scientific method and processes of science in science teaching. Hodson (1991) cites Dewey's 1916 argument that understanding scientific method is more important than the acquisition of scientific knowledge.

British educator Frederick Westaway (1929) was quite direct in his influential science teaching methods book with the clever title *Science Teaching: What it Was—What it Is—What it Might Be*. This book includes a full chapter on the role of the history of science and another on the philosophic foundations of science. This chapter is surprisingly contemporary with suggestions that students "must now learn to examine the nature of scientific evidence, hypotheses, induction and laws…" (p. 386). Furthermore, students are warned to work at eliminating bias when forming judgments, that "our senses may deceive us" (p. 388) and that it is difficult to ensure "that the facts from which [we] reason are objective and untainted." Westaway continues by mentioning the importance of the problems of induction and the notion of tentativeness (the provisional aspect of science) in our models and ideas while alluding to the limits of science. At much the same time, Jaffe (1938), in his high school textbook *New World of Chemistry*, included nature of science objectives such as a willingness to swing judgment while experiments are in progress, willingness to abandon a theory when new evidence is available, and knowledge that scientific laws may not be the ultimate truth.

When James Bryan Conant delivered his three influential Terry Lectures at Yale (Conant 1946), he advocated using history in science instruction by suggesting that all students must understand the tactics and strategies of science. One way to share such an understanding is for students to see science in action through its history. However, not until the second half of the twentieth century was the construct "nature of science" stated explicitly by Hurd (1960) as a major aim of science teaching:

> There are two major aims of science-teaching; one is knowledge, and the other is enterprise. From science courses, pupils should acquire a useful command of science concepts and principles. Science is more than a collection of isolated and assorted facts … A student should learn something about the character of scientific knowledge, how it has been developed, and how it is used (Hurd 1960, p. 34).

Several of the 1960s science curriculum projects in the United States attempted to move science instruction away from the typical focus on "what do scientists know?" to an examination of the question "how do scientists know?" Klopfer's (1964–1966) *History of Science Cases* and Schwab's seminal contributions to the *Biological Science Curriculum Studies* in the early 1960s are important efforts illustrating both the process and products of science in formal curricula. Among the most effective example of such a curriculum was *Harvard Project Physics* which began in 1962 and resulted in three editions of the *Project Physics* text (Rutherford et al. 1970), a project chronicled in Holton's (2000) overview.

Robinson (1968) in his book *The Nature of Science and Science Teaching* prompted science educators to see the value of the philosophy of science in science teaching and learning. His book provided an overview of the nature of physical reality; aspects of physical description including probability, certainty, and causality; and view of the nature of science in various science disciplines. He concluded with considerations for the interplay between science instruction and the nature of science. Another pioneer, Martin (1972), in *Concepts of Science Education: A Philosophical Analysis*, reiterated several arguments put forward by Robinson for attending to NOS in science education. He reviewed many of the important concepts from the philosophy of science including the value of inquiry learning, the nature of explanation, and the character of observation both in science and in science teaching and learning. This quest engages us today as we endeavor to extract conclusions from those scholars whose work focuses on describing the scientific enterprise and transforming those descriptions into lessons giving students rich and accurate views of science.

Incorporating aspects of nature of science content in school science has been widely embraced by organizations such as the Association for Science Education (1981) in Britain and organizations in the United States such as the National Science Teachers Association (1995, 2000, 2012), the American Association for the Advancement of Science (1990, 1993), and the National Research Council in the *National Science Education Standards* (1996) and in many international standards documents developed to guide science teaching and learning in classrooms. The American Association for the Advancement of Science publication *Science for all Americans* (AAAS, 1990) prominently featured the history and nature of science in science education efforts, devoting a full chapter to both. The US *Next Generation Science Standards* (Achieve 2013), as previously noted, overtly features NOS (regrettably in an appendix) along with recommendations that science instruction should focus on communicating science content, science, and engineering practices.

In 1987, reflecting the increasing scholarly interest in NOS, a new professional association was established—the International History, Philosophy and Science Teaching Group (IHPST)—which sponsors regional and international conferences and a well-regarded journal, *Science & Education*, that has effectively become the journal of record for work at the intersection of NOS and science teaching. NOS presentations at both practitioner and academic science education conferences are increasingly well-attended indicating that interest in this area continues to grow. Certainly contemporary science educators would agree that encouraging students to understand science, its presuppositions, values, aims, and limitations should be a central goal of science teaching. As Shamos (1995) suggested in *The Myth of Scientific Literacy*, knowledge of science content itself may not be necessary for obtaining science literacy, but understanding the nature of science *is* prerequisite to such literacy.

1.4 Rationales for the Inclusion of NOS in Science Instruction

Many scholars (Allchin 2013; Driver et al. 1996; Duschl 1990, 1994; Hodson 1986, 1988, 2014; Matthews 1989, 1994, 2015) have suggested that learning about NOS will promote a variety of important outcomes that serve as rationales for NOS instruction. Admittedly, not all rationales offered are necessary supported by empirical studies, but each presents a degree of face validity. We have examined this and other literature and have drawn on our experience to suggest the following reasons for the value of accurate NOS understanding. Each rationale offers a distinct significance for understanding NOS but is not necessarily mutually exclusive.

1.4.1 NOS Understanding is Fundamental for Understanding Science

Some content is so central to a field of study that ignoring it in instruction could be considered a matter of educational malpractice. For instance, instruction regarding cells, ecology, and biological evolution must be part of any course that can honestly be said to be an introduction to biology. A course titled introductory chemistry must address atoms, atomic theory, and other ideas that are at the heart of chemistry. Likewise, any science course is simply incomplete if it does not address NOS issues and related ideas. Simply put, NOS is fundamental to any conception of a science *education*. Joseph Schwab, philosopher and science educator, strongly recommended that science instruction place greater emphasis on what scientists do and how science works. He and others have lamented that science is often taught as an "unmitigated rhetoric of conclusions in which the current and temporal constructions of scientific knowledge are conveyed as empirical, literal, and irrevocable truths" (Schwab 1964, p. 24).

In support of this rationale, *Benchmarks for Science Literacy* (AAAS 1993) reminds us that NOS knowledge can provide something of the epistemological foundations of science within the school science experience:

> When people know how scientists go about their work and reach scientific conclusions and what the limitations of such conclusions are, they are more likely to react thoughtfully to scientific claims and less likely to reject them out of hand or accept them uncritically.… They can follow the science adventure story as it plays out during their lifetimes. (p. 3)

McCain and Segal (1982) write that, "Since [science] touches almost every facet of our life, educated people need at least some acquaintance with is structure and operation" (p. v). In summary, understanding how science operates is intrinsically important in any characterization of a well-educated and scientifically literate person.

1.4.2 NOS Understanding Nutures Students' Interest and Encourages Appreciation for Science

This rationale is rooted in the affective domain and is important for nurturing students' latent interest in science and perhaps encouraging them in their study of science and in pursuit of science-related degrees. Tobias (1990) reported that many high-performing university science students—those she calls the second tier—opted out of science, lamenting that science classes ignore the historical, philosophical, and sociological foundations of science, particularly the creative aspects of science. Moreover, interest often promotes better attitude and a higher degree of attention, both which impact learning. Addressing NOS when teaching science content can humanize science and convey the practice of science as a collaborative puzzle-solving adventure to understand nature.

Clough et al. (2010) report that among 85 biology majors who read short historical stories addressing how science ideas were developed and came to be accepted, 79 stated that doing science research appears more interesting that they previously thought. Thirty-six of the 85 stated they were more interested in science as a career, while 48 of the majors reported no change in their interest in a science career. In a similar study at the secondary school level, Reid-Smith (2013) reported that 41% of 500 students who read short historical science stories that accurately portrayed NOS found the science content more interesting, while 44% reported no impact on their interest, and 37% reported that science was more interesting than they previously thought, while 47% reported no change in how interesting science appeared to them. Hong and Lin-Siegler (2012) in a study involving 271 high school students reported that those students who learned about scientists' struggles developing the science ideas being taught to them had greater interest in science, improved their delayed recall of the key science ideas, and improved their ability to solve complex problems that required deeper conceptual understanding.

The next two rationales (utility for practice and citizenship) are related in that NOS may be recommended for its usefulness within science and in life generally; we will discuss each separately because the target of the application of NOS is distinct in each domain.

1.4.3 NOS Knowledge Can Assist Students and Scientists: NOS has Practical Utility

This rationale is founded on the principle that knowing how science works is important to two groups: students learning about science in school settings and scientists applying the "rules" of the game of science as they make in fundamental discoveries. Next we will consider the importance of NOS understanding to those in each of these groups.

We believe that school science should provide opportunities for students to function as much like scientists as possible. However, we recognize that students have not had the life experiences of scientists and therefore will "see" the world in the same way as do scientists. When students apply an accurate understanding of the history and nature of science, they are more likely to see their laboratory and field experiences in a more authentically scientific fashion.

For instance, when students working in the laboratory (also called practical work) are confused that their results do not precisely match those in their textbook, their understanding of idealization will prove useful. Those with a strong background in NOS know that the ideas and principles in science are often stated from the way they operate in ideal settings. Newton's laws of motion are an excellent example. Newton tells us that a rolling object will continue to move, but we recognize that in the real world, friction interferes and brings the object to a stop. Pendulum motion, as described in textbooks, is also idealized so that what students "see" in the laboratory may be somewhat at odds with what they read.

Another vital point is that students must understand that data do not "tell" anyone anything. Observers must personally and collectively make sense of data. Such an understanding will help students more confidently grapple with their own data. These and other NOS ideas can assist us all in making sense of and more productively engage in their school laboratory and field experiences.

Finally, only if students understand the overarching ideas that govern science, will they be able to operate more like scientists do. For instance, there are many shared methods of science including induction, deduction, and inference along with a host of process skills such as observation, measuring, and communicating. In addition, knowledge of the two main purposes of science—forming generalization and proposing explanations—can guide the progress of science. When students are engaged in scientific work in the school laboratory, they must know what acceptable practices are and use them consistently. We recognize that this justification for the inclusion of NOS in the curriculum has a somewhat circular nature because it combines both "learning NOS" and "using NOS," but these do not have to be visualized as separate goals.

Learners will be better "student-scientists" when they have foundation knowledge of many of the recommended elements associated with NOS. At the same time, students will have opportunities to learn more about key NOS elements when they are engaged in hands-on and other practical learning. This is particularly true in classrooms facilitated by teachers who value and understand NOS personally and use the laboratory as a place both to teach about NOS and provide practice in applying NOS principles.

We can now turn our attention to another group who would benefit from a firm understanding of NOS, practicing scientists. Stanley (2016) also puts forward several ways that understanding the history and nature of science can assist the actual practice of science. Among these is acknowledging the diversity of approaches and ideas in the past and how they assisted in pushing forward what was then the frontiers of science. He suggests that the awareness of novel approaches and ways of thinking can, in turn, assist current scientists in reexamining what is known in their efforts to push forward today's frontiers. It is true that even without NOS content included in all formal science learning opportunities, those who become scientists will learn how science functions by trial and error and intuition. If someone who purports to be a scientist is engaging in practices too far outside the realm of science, they will be excluded from the mainstream. A reasonable utilitarian justification for the inclusion of NOS in the science curriculum is that it may produce better scientists faster.

1.4.4 NOS Understanding is Vital for Citizenship

An understanding of how science functions and applying that understanding to both everyday thinking and informed citizenship decisions is what Driver et al. (1996, p. 18) called the "democratic argument" in support of NOS in the science curriculum. On this point, we might apply the delightful compound German term mentioned by Kötter and Hammann (2017), *Bewertungskompetinez*, defined as "the competency to make informed ethical decision in scientific contexts" (p.451). It is difficult to imagine that this label will come into widespread use, but this is precisely the meaning associated with this rationale for including NOS in the curriculum. For instance, NOS understanding plays a role in socio-scientific thinking regarding global climate change (Clough and Herman 2017; Herman 2015) and rejecting efforts of creationists/intelligent design proponents to thwart the teaching of biological evolution. NOS understanding can also assist in combating anti-science, irrationality, and scientism (the notion that science can address all problems) that plagues contemporary society.

As another example, consider the following "democratic" uses that might be made of NOS knowledge. Evidence exists (Ryan and Aikenhead 1992) that science is often confused with engineering and technology leading the public to support science because they wrongly see it as providing society with gadgets, vaccines, and other practical outcomes that improve everyday life. However, basic science research is not directly concerned with practical societal outcomes, but rather an understanding of the natural world for its own sake. The public's failure to see the importance of basic research in technological innovations is evident in citizens' and policy-makers' reluctance to fund basic research (Tyson 2011; Elmer-Dewitt 1994).

Shamos (1995) and Driver et al. (1996) add an interesting element to this rationale for NOS with their suggestion that students must understand who the experts are regarding science content and which experts ought to be trusted. Nonscientists rarely possess the expertise to judge the veracity of scientific conclusions, but NOS knowledge can assist in sorting out well-established consensus in the scientific community from individuals or groups that seek to sew doubt about any scientific conclusions relevant for personal and societal decision-making.

1.4.5 *NOS Knowledge Supports the Learning and Teaching of Traditional Science Content*

Matthews (1994) provides examples illustrating how NOS understanding places science teachers in a better position to implement conceptual change models of instruction and students in a better position deeply to understand certain science content. In the earlier noted study by Clough et al. (2010), of the 85 students experiencing short stories that accurately portrayed the development and acceptance of fundamental science ideas, 65% of them self-reported that the stories increased their understanding of the science content. Arya and Maul (2012) reported that of 209 middle school students, those experiencing science instruction via narrative accounts of scientists' work achieved higher conceptual understanding and knowledge retention of the relevant science content. Students from socioeconomically disadvantaged backgrounds benefitted even more. The authors speculate that their experimental approach may promote greater attentiveness to the conceptual content. Herman et al. (2019b) reported significant and moderate to moderately large associations existed between the accuracy and contextualization of students' NOS views and the complexity of their trophic cascade explanations. Much evidence (Dagher and BouJaoude 1997; Rudolph and Stewart 1998; Johnson and Peeples 1987; Rutledge and Warden 2000; National Academy of Sciences 1998; National Academy of Science and Institute of Medicine 2008; Smith 2000) supports the contention that NOS understanding assists in teaching and learning about biological evolution.

Having students study the process of historical conceptual development in science may also be useful to students in evaluating their own prior ideas (Wandersee 1986). For example, often students' ideas parallel that of early scientific ideas, as has often been the case in science. The persistence of students' naive ideas in science suggests that teachers could use the historical development of scientific concepts to help illuminate the conceptual journey students must make away from their own naive misconceptions.

1.5 A Brief Overview of the State of Current NOS Education Research

Even a cursory look at articles appearing in science education journals during the past three decades demonstrates extensive and increasing attention to issues regarding NOS teaching and learning. Sessions featuring discussions of NOS learning are common at professional science education conferences and are typically well-attended. Clearly, NOS-related scholarship and implications for practice remain of significant interest to many involved in science teaching and learning. We know much about effective instruction with respect to NOS, but many challenges remain as will be detailed in Chap. 4.

Thus, any satisfactory "review of the literature" would either have to be highly focused or, as it has been said elsewhere, a kilometer wide and a centimeter deep (or a mile wide and inch deep if you prefer). Colleagues writing about NOS have engaged in focused reviews of literature related to a specific issue (e.g., Abd-El-Khalick and Lederman 2000; Deng et al. 2011), while others such as Lederman (2007), Lederman and Lederman (2014) in chapters in the two volumes of the *Handbook of Research in Science Education* and Matthews (2014) in his extensive multivolume, multiauthor *International Handbook of Research in History, Philosophy and Science Teaching* have produced much broader reviews. Both approaches are beyond the scope of this chapter, but we recommend attention to these and other reviews. Instead, here, we provide a broad overview of the kinds of scholarly work in NOS education during the past two decades and end with a summary of what has been well-established regarding NOS teaching and learning.

Using a qualitative approach to determine the kinds of NOS research appearing in the scholarly literature during the past 20 years, Nouri et al. (2017) examined 438 articles appearing in major science education research journals and propose 9 categories in which NOS scholarship may be classified. These include (1) ways to teach NOS to students, (2) teaching NOS to educators, (3) analyses of classroom practices featuring NOS, (4) development of NOS assessment tools, (5) analyses of NOS instructional materials, (6) nonempirical commentaries on NOS such as the debate about NOS content, (7) the relationship of NOS understanding to other science content such as evolution, (8) investigations of scientists' and educators' views of NOS, and (9) analyses of topics and science content that might assist in communicating aspects of NOS. In addition to making apparent the intense scholarly attention to NOS in science education, this study made apparent that the value of NOS is well-established and that researchers now focus primarily on efforts to promote and improve NOS teaching and learning.

Empirical work regarding NOS instruction conducted during the past three decades has largely coalesced in support of the following well-substantiated claims (Lederman 2007):

- Students at all levels do not typically possess "adequate" conceptions of NOS.
- K-12 teachers do not typically possess "adequate" conceptions of NOS.
- Conceptions of NOS are best learned through explicit, reflective instruction as opposed to implicitly through experiences with simply "doing" science.
- Teachers' conceptions of NOS are not automatically and necessarily translated into classroom practice.
- Teachers do not regard NOS as an instructional outcome of equal status with that of "traditional" subject matter outcomes.

In addition, arguments and evidence are increasingly making clear that NOS instruction should occur in a variety of contexts that assist learners in more deeply understanding and flexibly applying the NOS (Bell et al. 2016; Clough 2006; Herman 2018). Further scholarship addressing NOS in science education can presume these well-established claims and direct efforts to promote and improve NOS teaching and learning, as well as other issues that are not yet settled.

1.6 Taking Stock and Considering the Future of NOS in the Science Curriculum

This chapter and chapters to come make clear that a metaphorical glass representing NOS in science education could either be described as half full or half empty. Optimistically, advocacy for NOS teaching and learning remains high among science educators and increasingly with science teachers. Few now argue with the proposition that school science experiences should include significant attention to accurately portraying the NOS. Standards documents speak to the importance of NOS teaching and learning, and much is now well-established about the state of NOS teaching and learning and what effective NOS instruction entails. This and other books offer many ways to engage students in discussions related to specific NOS elements.

NOS pessimists, on the other hand, may find the proverbial glass half empty, a view that is occasionally hard to refute. Despite the presence of well-reasoned rationales, extensive scholarship, and efforts to promote NOS instruction, science teachers and science curricula largely remain rigidly bound to a tradition of communicating the facts or end products of science while generally neglecting or failing to prominently promote accurate NOS understanding. Little of what is known about accurate and effective NOS instruction is widely implemented in science classrooms, and science teacher preparation and professional development efforts targeting NOS instruction are woefully inadequate (Backhus and Thompson 2006). Even current science education standards documents rarely provide and/or emphasize overt NOS learning outcomes (Höttecke and Silva 2011; Olson 2018). Thus, much remains to be done in promoting accurate and effective NOS teaching.

One of the challenges to promoting attention to NOS in school science is that, with rare exceptions, teachers, school administrators, parents, and policy-makers did not experience accurate NOS instruction in their own schooling, and thus, they do not see it as a crucial outcome of science education. This makes science teacher education and professional development efforts directed at NOS teaching and learning all the more important. Beyond promoting a robust understanding of NOS content and pedagogy, science teacher education efforts must first and foremost convince teachers of the crucial role NOS plays in teaching, learning, and citizenship (Herman et al. 2019a). Unless teachers feel compelled to accurately and effectively teach NOS, no amount of effort to improve their NOS content and pedagogy will improve the current state of NOS teaching and learning.

That said, teachers can hardly accurately teach what they do not understand. The importance of teachers' NOS understanding can be summarized by quoting Hollon et al. (1991) who tell us that "…science teachers must develop knowledge that enables them to make two types of decisions—curricular decisions and instructional decisions" (p. 149). Shulman (1986) further reminds us that teachers' knowledge can be divided into three broad categories—pedagogical, curricular, and subject matter—and defines subject matter knowledge as a discipline's facts, principals, *and* structure. NOS, of course, addresses issues related to the structure of science.

For instance, consider this definition of *pedagogical content knowledge* (PCK) (Shulman 1986) in the context of science teaching:

> Teachers must not only be capable of defining for students the accepted truths in a domain. They must also be able to explain why a particular proposition is deemed warranted, why it is worth knowing and how it relates to other propositions, both within the discipline and without, both in theory and in practice. (p. 9)

In science teaching, PCK is a synergistic amalgamation of science and NOS content knowledge, pedagogical skills, knowledge of curricular and instruction tools, use of analogies, and understanding of students' thinking all brought to bear in instructional decision-making to convey subject matter in a way that makes it comprehensible to learners. This means is that PCK applies to the teaching of all content, including NOS. Abd-El-Khalick (1997) first introduced the idea of NOS PCK noting that science teachers must possess an understanding of science and NOS content that is linked to methods for incorporating it into NOS instruction. NOS PCK also includes decision-making regarding how deeply NOS ideas can and should be addressed with students (see also Abd-El-Khalick 2013).

The challenge therefore is for science teacher educators to create learning experiences where science teachers learn about NOS in ways that can be translated into meaningful and effective classroom experiences and appropriate classroom discourse about the nature of science. That this can be accomplished in typical preservice science teacher education programs possessing one or two methods courses is highly improbable. Herman et al. (2013) followed graduates of an extensive and demanding science teacher education program and reported that 11 of the 13 participants were teaching NOS 2–5 years after graduation, and 9 of the 13 were doing so at moderate to high levels. Thus, the burden is on science teacher educators to bolster all science teacher education efforts directed at accurate NOS teaching and learning.

Of course, beyond the realm of teacher education, there are many other considerations that require our attention as we collectively continue to advocate for NOS inclusion in science instruction. Many of these are implied by the topics found in this book (more robust assessment tools, improved NOS learning standards, research-based recommendations linked to NOS learning progressions, and considerations for the role of NOS in higher education science learning environments). However, as readers of this book will see, we have learned much about NOS teaching and learning. For those who see the NOS as a “glass half full,” there is reason to be enthusiastic about the future of NOS even as we recognize that much effort remains on a variety of fronts. Those involved in this book look forward to the day when the inclusion of NOS content in science class needs no more justification than does the study of ecology in biology, motion in physics, periodic law in chemistry, and the rock cycle in geology. NOS is the content that ties the sciences together.

Years ago, evolutionary biologist Theodosius Dobzhansky (1973, p. 125) uttered the famous phrase that “nothing in biology makes sense expect in the light of evolution.” Today, we could just as earnestly state that nothing in science makes sense except in the light of the nature of science. Let us hope that this statement guides science instruction as effectively as Dobzhansky's has impacted the science of biology and biology instruction.

References

Abd-El-Khalick, F. (1997) *Improving prospective and practicing science teachers' conceptions of the nature of science.* Unpublished scholarly library research paper presented to the faculty and doctoral students. Department of Science and Mathematics Education, Oregon State University, Corvallis, OR.

Abd-El-Khalick, F. (2013). Teaching with and about nature of science, and science teacher knowledge domains. *Science & Education, 22*(9), 2087–2107.

Abd-El-Khalick, F., & Lederman, N. G. (2000). Improving science teachers' conceptions of the nature of science: A critical review of the literature. *International Journal of Science Education, 22*(7), 665–701.

Achieve. (2013). *Next generation science standards: For states, by states*. Washington, DC: The National Academies Press.

Allchin, D. (2013). *Teaching the nature of science: Perspectives and resources*. St. Paul: SHiPS Education Press.

American Association for the Advancement of Science [AAAS]. (1990). *Science for all Americans*. New York: Oxford University Press.

American Association for the Advancement of Science [AAAS]. (1993). Benchmarks for *Science Literacy.* New York: Oxford University Press.

American Association for the Advancement of Science [AAAS]. (2001). *Atlas of science literacy: Mapping K-12 learning and goals*. Washington, DC: Author.

Arya, D. J., & Maul, A. (2012). The role of the scientific discovery narrative in middle school science education: An experimental study. *Journal of Educational Psychology, 104*(4), 1022–1032.

Association for Science Education. (1981). *Education through science: An ASE policy statement*, Hatfield, England.

Backhus, D. A., & Thompson, K. W. (2006). Addressing the nature of science in preservice science teacher preparation programs: Science educator perceptions. *Journal of Science Teacher Education, 17*(1), 65–81.

Bell, R. L., Mulvey, B. K., & Maeng, J. L. (2016). Outcomes of nature of science instruction along a context continuum: Preservice secondary science teachers' conceptions and instructional intentions. *International Journal of Science Education, 38*(3), 493–520.

Central Association of Science and Mathematics Teachers (CASMT). (1907). A consideration of the principles that should determine the courses in biology in the secondary schools. *School Science and Mathematics, 7*, 241–247.

Clough, M. P. (2006). Learners' responses to the demands of conceptual change: Considerations for effective nature of science instruction. *Science & Education, 15*(5), 463–494.

Clough, M. P., & Herman, B. C. (2017). The role of history and nature of science in climate change teaching and learning. In D. Shepardson, A. Roychoudhury, & A. Hirsch (Eds.), *Teaching and learning about climate change: A framework for educators*. New York: Routledge.

Clough, M. P., Herman, B. C., & Smith, J. A. R. (2010, January 14–16). *Seamlessly teaching science content and the nature of science: Impact of historical short stories on post-secondary biology students*. Association for Science Teacher Education International Conference, Sacramento, CA. https://storybehindthescience.org/research.html

Conant, J. B. (1946). *On understanding science: An historical approach*. New Haven: Yale University Press.

Dagher, Z. R., & BouJaoude, S. (1997). Scientific views and religious beliefs of college students: The case of biological evolution. *Journal of Research in Science Teaching, 34*(5), 429–445.

Deng, F., Chen, D., Tsai, C., & Chai, C. (2011). Students' views of the nature of science: A critical review of the literature. *Science Education, 95*(6), 961–999.

Dobzhansky, T. (1973). Nothing in biology makes sense except in the light of evolution. *The American Biology Teacher, 35*(3), 125–129. https://doi.org/10.2307/4444260.

Driver, R., Leach, J., Millar, R., & Scott, P. (1996). *Young peoples' images of science*. Buckingham: Open University Press.

Duschl, R. A. (1990). *Restructuring science education: The importance of theories and their development*. New York: Teachers College Press.

Duschl, R. A. (1994). Research on the history and philosophy of science. In L. G. Dorothy (Ed.), *Handbook of research on science teaching and learning* (pp. 445–455). New York: Macmillan.

Einstein, A. (1934/1982). *'On the method of theoretical physics'*, Herbert Spencer lecture delivered at Oxford, June 10, 1933. Mein Welbild (1934), Amsterdam: Querido Verlag. "Ideas and Opinions" (1982) New York: Crown.

Elmer-Dewitt, P. (1994). Don't tread on my lab. *Time, 143*, 44–45.

Herman, B.C. (2015). The influence of global warming science views and sociocultural factors on willingness to mitigate global warming. *Science Education 99*(1), 1–38.

Herman, B. C., Clough, M. P., & Olson, J. K. (2013). Teachers' NOS implementation practices two to five years after having completed an intensive science education program. *Science Education, 97*(2), 271–309.

Herman, B. C. (2018). Students' environmental NOS views, compassion, intent, and action: Impact of place-based socioscientific issues instruction. *Journal of Research in Science Teaching, 55*(4), 600–638.

Herman, B. C., Olson, J. K., & Clough, M. P. (2019a). The role of informal support networks in teaching the nature of science. *Research in Science Education, 49*, 191–218. https://doi.org/10.1007/s11165-016-9610-2.

Herman, B. C., Owens, D. C., Oertli, R. T., Zangori, L. A., & Newton, M. H. (2019b). Exploring the complexity of students' scientific explanations and associated NOS views within a place-based socioscientific issue context. *Science and Education, 28*(3), 329–366.

Herron, M. D. (1969). Nature of science: Panacea or Pandora's box. *Journal of Research in Science Teaching, 6*, 105–107.

Hodson, D. (1986). Rethinking the role and status of observation in science curriculum. *Journal of Curriculum Studies, 18*, 381–396.

Hodson, D. (1988). Toward a philosophically more valid science curriculum. *Science Education, 72*, 19–40.

Hodson, D. (1991). The role of philosophy in science teaching. In M. R. Matthews (Ed.), *History, philosophy and science teaching: Selected readings*. New York: Teachers College Press.

Hodson, D. (2014). Nature of science in the science curriculum: Origin, development, implications and shifting emphases. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 911–970). Dordrecht: Springer.

Hollon, R., Roth, K. J., & Anderson, C. W. (1991). Science teachers' conceptions of teaching and learning. In J. Brophy (Ed.), *Advances in research on teaching: Teachers' knowledge of subject matter as it related to their teaching practice* (Vol. 2, pp. 145–185). Greenwich: Jai Press.

Holton, G. (2000). The project physics course, then and now. *Science & Education, 12*, 779–786.

Hong, H., & Lin-Siegler, X. (2012). How learning about scientists' struggles influences students' interest and learning in physics. *Journal of Educational Psychology, 104*(2), 469–484.

Höttecke, D., & Silva, C. C. (2011). Why implementing history and philosophy in school science education is a challenge: An analysis of obstacles. *Science & Education, 20*(3–4), 293–316.

Hurd, P. D. H. (1960). Summary. In N. B. Henry (Ed.), *Rethinking science education: The fifty-ninth year-book of the National Society for the study of education* (pp. 33–38). Chicago: University of Chicago Press.

Jaffe, B. (1938). The history of chemistry and its place in the teaching of chemistry. *Journal of Chemical Education, 15*, 383–389.

Johnson, R. L., & Peeples, E. E. (1987). The role of scientific understanding in college. *The American Biology Teacher, 49*, 93–96.

Klopfer, L. (1964–1966). History of science cases (HOSC), Chicago, Science Research Associates.

Kötter, M., & Hammann, M. (2017). Controversy as a blind spot in teaching nature of science. *Science & Education, 26*, 451–482.

Laudan, L., Donovan, A., Laudan, R., Barker, P., Brown, H., Leplin, J., Thagard, P., & Wykstra, S. (1986 November). *Testing theories of scientific change* (Synthese, vol 69(2), pp. 141–223). Dordrecht: D. Reidel Publishing.

Lederman, N. G. (2002). The state of science education: Subject matter without context. *Electronic Journal of Science Education, 3*(2). unr.edu/homepage/jcannon/ejse/ejse.html.

Lederman, N. G. (2007). Nature of science: Past, present, and future. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education*. Mahwah: Lawrence Erlbaum Associates.

Lederman, N. G., & Lederman, J. S. (2014). Research on teaching and learning of nature of science. In N. Lederman & S. Abell (Eds.), *Handbook of research on science education* (pp. 600–620). New York: Routledge.

Martin, M. R. (1972). *Concepts of science education: A philosophical analysis*. Greenview: Scott, Foresman.

Matthews, M. R. (1989). A role for history and philosophy in science teaching. *Interchange, 20*, 3–15.

Matthews, M. R. (1994). *History, philosophy, and science teaching: A useful alliance*. New York: Routledge.

Matthews, M. R. (1997). Editorial. *Science & Education, 6*, 323–329.

Matthews, M. R. (1998). In defense of modest goals when teaching about the nature of science. *Journal of Research in Science Teaching, 35*(2), 161–174.

Matthews, M. R. (2012). Changing the focus: From nature of science (NOS) to features of science (FOS). In M. S. Khine (Ed.), *Advances in nature of science research: Concepts and methodologies* (pp. 3–26). Dordrecht: Springer.

Matthews, M. R. (Ed.). (2014). *International handbook of research in history, philosophy and science teaching*. Boston: Springer Academic Publishers.

Matthews, M. R. (2015). *Science teaching: The contributions of history and philosophy of science*. New York: Routledge.

McCain, G., & Segal, E. M. (1982). *The game of science*. Belmont: Wadsworth.

McComas, W. F. (1998). The principal elements of the nature of science: Dispelling the myths. In W. F. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 53–73). Boston: Kluwer (Springer) Academic Publishers.

McComas, W. F. (2004). Keys to teaching the nature of science: Focusing on the nature of science in the science classroom. *The Science Teacher, 71*(9), 24–27.

McComas, W. F., & Nouri, N. (2016). The nature of science and the next generation science standards: Analysis and critique. *Journal of Science Teacher Education, 27*(5), 555–576.

McComas, W. F., Clough, M. P., & Almazroa, H. (1998). The role and character of the nature of science in science education. In W. F. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 3–39). Boston: Kluwer (Springer) Academic Publishers.

National Academy of Sciences. (1998). *Teaching about evolution and the nature of science*. Washington, DC: National Academies Press.

National Academy of Sciences and Institutes of Medicine. (2008). *Science, evolution and creationism*. Washington, DC: National Academies Press.

National Research Council. (1996). *National science education standards*. Washington, DC: National Academy Press.

National Science Teachers Association. (1995). *A high school framework for national science education standards*. Arlington: Author.

National Science Teachers Association. (2000). *NSTA position statement: The nature of science*. Retrieved from: http://www.nsta.org/about/positions/natureofscience.aspx

National Science Teachers Association. (2012). *2012 NSTA standards for science teacher preparation*. Retrieved from: http://www.nsta.org/preservice/

Nouri, N., McComas, W. F., Saberi, M., & Oramous, J. (2017, January). *Focus and trends in nature of science research during the past twenty years*. Annual Meeting of the Association for Science Teacher Education. 2017, January. Des Moines, IA.

Olson, J. K. (2018). The inclusion of the nature of science in nine recent international science education standards documents. *Science & Education, 27*, 637–660. https://doi.org/10.1007/s11191-018-9993-8.

Osborne, J., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. (2003). What "ideas-about-science" should be taught in school science? A Delphi study of the expert community. *Journal of Research in Science Teaching, 40*(7), 692–720.

Reid-Smith, J. A. (2013). *Historical short stories as nature of science instruction in secondary science classrooms: Science teachers' implementation and students' reactions*. Unpublished doctoral dissertation, https://lib.dr.iastate.edu/etd/13633

Robinson, J. T. (1968). *The nature of science and science teaching*. Belmont: Wadsworth.

Rudolph, J. L., & Stewart, J. (1998). Evolution and the nature of science: On the historical discord and its implications for education. *Journal of Research in Science Teaching, 35*(10), 1069–1089.

Rutherford, F. J., Holden, G., & Walton, F. G. (1970). *Project physics*. New York: Holt, Rinehart and Winston.

Rutledge, M. L., & Warden, M. A. (2000). Evolutionary theory, the nature of science and high school biology teachers: Critical relationships. *American Biology Teacher, 62*(1), 23–31.

Ryan, A. G., & Aikenhead, G. S. (1992). Students' preconceptions about the epistemology of science. *Science Education, 76*(6), 559–580.

Schwab, J. J. (1964). The teaching of science as enquiry. In J. J. Schwab & P. F. Brandwein (Eds.), *The teaching of science* (pp. 31–102). Cambridge, MA: Harvard University Press.

Shamos, M. (1995). *The myth of scientific literacy*. New Brunswick: Rutgers University Press.

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher, 15*, 4–14.

Smith, M. U. (2000). The current status of research in teaching evolution II. Pedagogical issues. *Science & Education, 19*(6–8), 539–571.

Stanley, M. (2016). Why should physicists study history? *Physics Today, 69*(7), 38–44. https://doi.org/10.1063/PT.3.3235

Tobias, S. (1990). *They're not dumb: They're different: Stalking the second tier*. Tucson: Research Council.

Tyson, N. DeG. (2011, January 20). The moon, the tides and why Neil DeGrasse Tyson is Colbert's god: A conversation about communicating science, *The Science Network*. http://thesciencenetwork.org/programs/the-science-studio/neil-degrasse-tyson-2. Retrieved 17 October 2018.

van Dijk, E. M. (2011). Portraying real science in science communication. *Science Education, 95*, 1086–1100.

Wandersee, J. (1986). Can the history of science help science educators anticipate students' misconceptions? *Journal of Research in Science Teaching, 23*, 581–597.

Welch, W. W. (1984). A science-based approach to science learning. In D. Holdzkom & P. B. Lutz (Eds.), *Research within reach: Science education* (pp. 161–170). Washington, DC: National Science Teachers' Association.

Westaway, F. W. (1929). *Science teaching: What it was – What it is – What it might be*. London: Blackie and Son, Ltd.

Chapter 2
Considering a Consensus View of Nature of Science Content for School Science Purposes

William F. McComas

2.1 Introduction

In recent decades, discussions about nature of science (NOS) generally have moved from consideration of whether we should teach about NOS to the more productive conversation of how to include NOS in the science curriculum. However, the transition in this conversation has not been completely smooth. This chapter will discuss what has come to be called the consensus view of NOS for school purposes; simply put, this is the somewhat informal process by which recommendations have been offered and accepted by the science education community reflected in and textbooks and featured in science classrooms. There are no official leaders of the consensus camp, and there has never been a vote; in fact, this process is essentially organic and evolutionary. What is true is that the set of most frequently seen NOS topics has developed in much the same way as have recommendations for almost all other science content. Yet, this common process has been criticized frequently to the extent that some might think that we really do not know what elements of NOS should be taught. If true, this is unfortunate.

The strong recommendation that it is time to ensure that NOS is represented in science class has been distracted by several main arguments. One is what should this foundational domain of science be called (perhaps natures of science, nature of sciences, the nature of scientific knowledge, etc.), a topic discussed in the previous chapter. Second, and much more frustratingly, we have been slowed in including NOS in the science classroom with the continuing debate about what NOS elements should serve as learning objectives.

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_2

Some have suggested that the task of consulting with experts and defining a useful summary of important NOS elements is impossible. Others have stated that all existing (and perhaps any) NOS consensus views misrepresent and/or distort science. These are both highly suspected views and not at all helpful in moving our conversation in the direction of ensuring that NOS find a place in all science classrooms. At an introductory level, there are philosophical elements that link all the science disciplines. Furthermore, an instructional focus informed by accurate yet elementary NOS ideas does no more to distort science itself than a few chapters on the cell in a basic biology text distort the science of cellular biology.

Perhaps those in the non-consensus camp simply fail to understand the goals for NOS instruction and, perhaps, even the purpose of science instruction itself as introductory experiences in schools and higher education settings. Learners may or may not study science later at some more advanced level, so what we teach in terms of both traditional science content and NOS must reflect this reality. Perhaps some of our students will become scientists or even philosophers of science, but most will not. However, all students will – we expect – become contributing members of society, consumers of products and information, *and* voters. However, all students must learn something about science and its nature for the reasons suggested by Driver et al. (1996) and expanded on in Chap. 1. If students become particularly interested, there are opportunities for advanced training in the history and philosophy of science. The overarching NOS goal is that schools must support basic science literacy for all while still inspiring a few along a path to deeper future learning. Let us not become so enamored of the debate that we lose focus on its resolution and continue to block NOS instructional implementation.

This chapter and this entire book take the position that it is time to move on from both issues not because they have been finally put to rest but because the academic discourse, while interesting, may be preventing classroom inclusion of this vital science content. Even as we continue discussion of some NOS issues, science instruction will be strengthened when we ensure that students leave their science learning experiences with both knowledge of traditional science content that has always been an instructional focus and enough knowledge of NOS that students can understand and appreciate how science functions and what makes it a unique and productive way of knowing.

2.2 The Consensus Approach to Defining NOS for School Science Purposes

Chapter 4 features an extensive description and discussion of a specific set of NOS elements worthy of inclusion in school settings, but this chapter will focus on a review of the critiques regarding the consensus view of NOS. We will begin with some introduction and proceed to talk about four prominent objections – with some overlap – worthy of consideration. The discussion here is related to the analysis provided by Kampourakis (2016) who offered a somewhat parallel consideration of the debate.

As an introduction to this section, readers must know that there can be no divinely inspired and/or validated single set of recommendations for the aspects of NOS that we “know” are the right elements on which we should focus in science class. None of us who support any form of consensus can claim to know what aspects of NOS to recommend any more than we “know” that the biology curriculum should give students experience with the microscope. What we do know is that those with experience in schools, knowledge of the history and philosophy of science, and a desire to move a NOS teaching agenda forward rather than to continually wring our hands repeatedly revisit the same questions about “what NOS” to teach, “how much NOS to teach,” and “how to teach aspects of NOS.” Doing this thus far has resulted in a kind of paralysis of perfection that gets us nowhere. In fact, one could posit that those who are not interested in adding important NOS-related concepts to the science curriculum would take delight in this position held by some and conclude that there is no point in making any recommendations about NOS instruction until the science educators figure out how to proceed.

For decades, some of us have continued the process of deep consideration of what might be the core elements of the history and philosophy of science potentially worth considering as consensus aspects. One such set of recommendations came from a review of many international standards documents and has continued to evolve with the inclusion of suggestions from professional historians and philosophers of science and knowledgeable science educators. Hodson (2014) recently has unfairly and seemingly without evidence rejected such sets of NOS recommendations by saying “it is the sheer banality and unhelpfulness of some of the items that teachers find frustrating” (p. 921). We agree that teachers are often frustrated by NOS, but the reason for that frustration has little to do with the fact that science education experts have offered recommendations for what that NOS content might be. If anything, NOS recommendations have helped to energize and direct the conversation about the NOS content that should be featured in the science curriculum.

It is reasonable to ask what evidence exists that we would ever be satisfied just giving teachers some shorthand list and sending them on their way? What evidence exists that teachers, in fact, do find these NOS aspects unhelpful and or frustrating? After all, these elements are now featured in the US *Next Generation Science Standards* (Achieve 2013). Where is the evidence that those who offer any recommendations about what NOS to teach have suggested that a set of brief phrases comprises all there is to know about the underlying concepts? Learning objectives are frequently offered in the form of statements; NOS content is communicated in a similar fashion. Those of us who offer these recommendations fully understand that teacher education programs must prepare future science instructors to develop robust NOS PCK and that can only occur when teachers have opportunities to learn about the history and philosophy for themselves and engage in discussions about how to infuse the curriculum and classrooms with such content.

A frustrating view offered by Kötter and Hammann (2017) is a case in point. To summarize their main points, these colleagues see little utility in the consensus view of NOS (which they curiously call "GA") and suggest that we should be teaching the controversies regarding the nature and function of science. As they say, "controversies about the scope and limits of science should be considered in NOS teaching" (p. 451). Yes, there are controversies in the philosophy of science, and they are interesting, and I would never suggest that such a conversation is never appropriate for some students in some settings even in an introductory class. However, unless the school year becomes infinitely long and student interest grows exponentially, our job as science teachers is to share what is generally known with students. Certainly, we should teach all science content in engaging and interesting ways, but there is little profit in turning a wide-ranging introductory experience in science learning into an intense focus that might be more appropriate in a graduate seminar.

Good teachers will continually remind students that there is more to explore on any topic. Kötter and Hammann (2017) go on to suggest that "NOS education should generally help students examine … their own positions and not persuade them of a certain epistemic or science-reflective position" (p. 457). Yes, students come to us with deep misunderstandings (or sometimes no understanding) about how science works, and good teachers recognize that helping reveal and address their personal notions is an effective instructional technique. However, is the suggestion here to send the students on their way thinking that what they know about how science functions is as valid as what generations of historians, philosophers, and sociologists have told us about how science functions? The recommendation in this curious paper that we should give students opportunities to reflect is valid as is the suggestion that students might occasionally be confronted with controversial issues in the philosophy of science. However, it is impossible to endorse this as *the* way to teach about NOS. These authors mention the ploy of creationists who insist that we "teach the controversy" about evolution but fail to see that creationists do this to plant doubt generally regarding the reality of evolution. Should we do this with NOS as well? Should we teach the so-called controversy while suggesting – directly or indirectly – that we know nothing about the nature of science, or is it time to recognize that there are many notions and descriptions of how science functions that we can and really must agree on?

2.3 Objections to the Consensus Approach

In the next part of this chapter I will address what seem to be the major criticisms of the NOS consensus view. In the concluding section, each of the key NOS statements is explained in detail, for those interested in knowing more fully what each NOS recommendation involves. However, let us end here with another statement from Hodson (2014, p. 913), this one far more reasonable than the last, "the curricular importance of NOS understanding per se is no longer in dispute."

2.3.1 A List of Shared Practices Across all Sciences May Blur or Perhaps Misrepresent the Distinctions About How NOS Functions in the Individual Science Discipline

Scholars such as van Dijk (2011, 2012) and Duschl and Grandy (2012) point out that some aspects of the conduct of science and even its products are different when comparing one science discipline to another. This is true. Therefore, some (e.g., Samarapungavan et al. 2006; Schizas et al. 2016) argue that we should use the term "nature of the sciences" (NOSs) instead of NOS because the characteristics of how science functions differ somewhat from one science discipline to another. Yes, lawlike statements in biology may be typically probabilistic (they function some percentage of the time in the way described), whereas laws in the "hard sciences" like chemistry and physics function much more consistently and universally. In the case of biology, we have no idea if the generalizations (lawlike statement) described in living systems here on Earth operate anywhere else, since our experience with living things is quite bounded. But having students understand when ideas demonstrate lawlike character and others show theory-like character is the goal. The distinction between physical laws and biological generations is fascinating (Lange 2009; Waters 1998), and students could be directed to advanced thinking in this area, but so many of our graduates both from secondary and postsecondary education fail even to appreciate the most basic distinction between the notions of law and theory.

However, these authors go too far when they suggest that the philosophical distinctions from one discipline to another effectively negate making crosscutting recommendations about NOS as learning objectives. Thus, their valid point is not particularly useful in the context of science instruction where the goal is to infuse traditional science content with appropriate discussions of NOS. No one wants to "dumb down" NOS, but, at the same time, neither should we expect a university-level treatment of any content in introductory settings.

NOS elements recommended for inclusion in science classrooms are "big picture" notions and function similarly enough that they can be stated as crossing the boundaries of the individual sciences. For instance, a recommendation that students should learn the difference between laws and theories is still functional. We want students to understand the relationship between laws and theories, to know that they are not the same, and to recognize that they are both key products and tools of science. The distinctions regarding the nature of laws and theories within specific science disciplines can and should be made within those disciplines. A general statement recommending that students should understand the nature of laws (and lawlike statements) and theories unites the sciences in a reasonable fashion and does not negate or discourage discussion of subject-specific distinctions. In fact, just the opposite is true. Those teaching individual science disciplines should discuss how NOS functions there even as they make the point that the sciences have much in common with each other philosophically. The current colloquial statement that we should stay "out of the weeds" seems useful to evoke here. If we get so caught up in interesting but somewhat ancillary debates about how laws, for instance, function differently in life and physical sciences, students might fail to learn that generalizations and explanations are distinct things in science.

2.3.2 Most Suggestions for NOS Learning Goals are Focused on Only Widely Accepted Aspects of Nature of Science

This statement is true, expected, and desirable. Irzik and Nola (2011, p. 592) criticized the consensus view of NOS by stating that those advocating such a view believe that:

> We should teach students only those characteristics that are widely accepted either in the science standards documents and/or in the philosophy, history, sociology of science and science education literature and for that reason they are the least controversial aspects of the nature of science.

Irzik and Nola are correct, but the criticism is odd. Advocating the main and generally agreed-upon conclusions is what we do in education. In every school science experience, we teach what is widely applicable, interesting, and accepted (i.e., least controversial and most "settled" knowledge might be another way to say this). We typically do not teach much about the highly advanced aspects of any discipline in introductory classes. Frankly, it is hard to imagine any reason that this would not be the desired case, and this is particularly true with NOS. The statement provided by these dissenters can easily be read as a position of advocacy for consensus rather than a viable objection. In trying to find something useful in their criticism, it is easy to support the recommendation that knowledgeable teachers who have particularly interested students should entice them further by suggesting readings or offering the opportunity for conversation on more advanced and even controversial NOS issues. Again, we must remind readers that there is little NOS in school science now and there is precious little time to shoehorn anything else into the existing curriculum, so of course, we should teach the aspects of NOS upon which there is maximum agreement.

2.3.3 The Consensus View of NOS for Instructional Purposes May Be Incomplete

This view is quite reasonable, and in the spirit of self-correction in science, should a major element of NOS have been neglected, we can and should reopen the conversation. Irzik and Nola (2011, p. 592) state that "the consensus view has certain shortcomings and weaknesses. First, it portrays a too narrow image of science. For example, there is no mention of the aims of science or methodological rules in science." In this case, they are simply incorrect. The NOS recommendations illustrated in Fig. 3.1 of Chap. 3 in the following chapter include a discussion of the limits to the application of science, and the "tools and products of science" section provides much detail about induction, deduction, and so on. Again, if a major NOS element were excluded, there is no reason that those working in this area could not include it and reach out for a new consensus on NOS instructional goals. Perhaps the challenge here is that those offering objections to the consensus view lack the necessary expertise in science teaching and learning to propose instructional goals and are simply too close to the disciplines of history and philosophy of science themselves. For instance, one wonders what the botany chapter in a secondary-school text would include if only botanists and not science educators, teachers, and curriculum specialists were asked to describe the content.

Hodson and Wong (2014) seem to reject the consensus view of NOS for reasons of a curious notion they call orthodoxy. They state that:

> Those who disagree with the specification will be considered deviant. We have had orthodoxy before, in the view that science has an all-purpose, straightforward and reliable method of ascertaining the truth about the universe, with the certainty of scientific knowledge being located in objective observation, extensive data collection and experimental verification …. Orthodoxy, also, in the view that every scientist acts on every occasion in a rational, logical, open-minded and intellectually honest way, and always adopts a disinterested, value-free and analytical stance. Some of us fought long and hard to rid the curriculum of this particular orthodoxy. (p. 2644)

This is a baffling notion and seems based on the idea that the "consensus community" is ready to take on any dissenters and banish them from the discussion because we know that the conversation is complete, and the matter settled. This is certainly not true. If something has been misstated or is missing in any recommendations about NOS, such an issue should be corrected. Consensus building is not an infallible way of making decisions, but a half-century of scholarship and deliberation, engaged in by those who understand schools and students, seems a reasonable approach.

Hodson and Wong (2014) suggest that proponents of the consensus list have it wrong in describing some aspects of science itself and cite some examples. But, a review of Fig. 3.1 of Chap. 3 reveals the recommendation that NOS instruction should include some focus on the human elements of science including the issues of tentativeness and subjectivity, the challenges associated with "certainty," and the realization that humans bring their own biases to the act of investigation. These recommended NOS issues are discussed much more fully in the next chapter. Readers are reminded that no list or annotated figure can do justice to the complex issues of NOS recommended for instruction, but such lists and figures are occasionally unfairly criticized as simplistic by those who fail to recognize that these quick overviews are just the beginning of the discussion, not ends unto themselves.

In addition to the issue of orthodoxy, some, including Hodson and Wong (2014), suggest that some NOS issues are missing. That may be true in a sense, but when one considers issue of time, other demands of content coverage, and students' interests and readiness for learning, there must be limits on what NOS is included in science instructional plans. Certainly, there are many fascinating aspects of NOS that one might include in any proposal for inclusion in school science. Hodson and Wong (2014, p. 2645) specifically mention realism/instrumentalism when stating that they are "concerned that the consensus list seeks to exclude some of the 'big issues' with which philosophers of science have traditionally grappled." Those who offer suggestions for NOS content in any consensus plan have no strategic desire to exclude certain topics, and one supposes that, if Hodson and Wong had a "list," it would include instrumentalism and realism. Such additions are fine if those making the recommendations have evidence that the targeted learners can understand these notions, that there is time in the school calendar for such inclusion, and that failing to include these ideas would seriously diminish the overall picture of NOS desired. We all want to fight for the inclusion of our favoriate content elements in the school curriculum, but there is only so much time that can be devoted to any instructional goals no matter how interesting they are.

Erduran and Dagher (2014) criticize the consensus recommendations because of other specific omissions. For instance, they feel that most current NOS recommendations are incomplete because they fail to include political power structures, social organizations and interactions, and financial systems (presumably grant-making). Their point is well taken in one sense. Many of the consensus recommendations have failed specifically to include such matters, but the NOS domain *Human Elements of Science*, which targets interactions between society and science, most certainly presupposes such content if desired. Thus, the issues mentioned by Erduran and Dagher really are found within this consensus domain and perhaps should be mentioned more prominently and/or by noting that this domain has both individual and sociological dimensions.

The comments from Erduran and Dagher, Hodson and Wong, Irzik and Nola, and others are worthy of consideration, but we must continue to recognize that the goal of introductory science instruction is not to prepare fully fledged scientists or philosophers. If some sophisticated NOS issues are thought to be missing from any set of recommendations, we would do well to remember the impracticably of turning a high school science class into an intense forum in NOS before agreeing to include every recommended element of NOS. As with traditional science content, decisions must be made about what to teach, and some good things will inevitably be relegated to the cutting-room floor. Of course, we have collectively been doing this for generations through a didactic and vigilant transposition process as recommended by Chevallard (1989).

2.3.4 The Foundation for Establishing the Consensus View of NOS Is Faulty

The principal proponents of this position are Erduran and Dagher (2014), who are enamored of the family resemblance approach (FRA) advocated first by Wittgenstein generally (1953/2009) and later championed by Irzik and Nola with respect to NOS. The basic notion of FRA is that seemingly disparate things may be connected through family resemblance even though no one feature is found in all cases.

Wittgenstein often cited the example of games. Games are all related by family resemblance, but, according to Wittgenstein, no one feature appears in all things called games. While I am no expert in Wittgenstein's philosophy, it seems that all games have rules for play – although other things also have rules. Does this somewhat negate the example?

It is true that defining what science is can be tricky, particularly when confronted with a pseudoscience such as astrology, which may look superficially like science. However, when we dig more deeply, astrology fails dismally, particularly with respect to the NOS principles of evidence and ability to make predictions found in sciences with well-established laws. If we apply the FRA approach to science, we see a large variety of overlap, thus meeting one of Wittgenstein's requirements; however, it seems that the NOS consensus elements do represent general features common to all sciences, even if they do not operate in precisely the same fashion. As stated, we know that laws in biology and laws in the physical sciences are distinct in their predictive ability, but lawlike statement (i.e., generalizations) exists across the spectrum of the science disciplines. In their Table 2.2 (p. 26), Erduran and Dagher (2014) establish their view of science through FRA which looks very much like the view of science represented by the elements of NOS recommended by consensus. Perhaps the rhetoric regarding the superiority of the FRA approach is much ado about nothing but is an unintended distraction in our quest to help educators understand what they should be teaching about NOS.

Those who reject the consensus view of NOS do not add much of practical importance to the shared goal of including aspects of NOS into school science programs. In fact, if one were to accept their conclusion that the science education community has not yet decided on the NOS aspects to be included in school science programs, NOS would be relegated to an even less prominent position in science classrooms than it has now. It makes more sense to take the positions of Kampourakis (2016) who characterizes the consensus view as "pragmatics and effective" (p.667) and Southerland et al. (2006) whose views summarize the issue nicely by stating:

> Despite the heated discussions as to the finer points of [the] most appropriate portrayal of the nature of science…the consensus view of NOS is a visceral component of current science education reform efforts. Given its prominence, the consensus view of NOS has played an important role in shaping the preparation of science teachers in recent years and so it serves as the framework both for the instructional approach used in this research and our analytical lens. (pp. 877–878)

2.4 Further Considerations: The Distinction between Declarative and Procedural NOS Knowledge

Another misunderstanding, on the part of some, regarding proposed sets of NOS learning goals is an unstated implication that such goals imply or demand any way of teaching. This point is extraordinarily important but frustrating. It is often stated that the consensus list of NOS objectives is inappropriate because it is "just a list."

This chapter should demonstrate that behind a simple recitation of NOS learning goals (i.e., the list), instructors must have a sophisticated understanding before they engage students in NOS learning. Of course, this is true with most educational objectives which are often briefly stated. In turn, skilled educators are expected to take such objectives as a goal and develop ways to engage students in rich and varied learning experiences related to them. However, since this issue of the "list" seems to be raised frequently, let me emphatically state we do *not* advocate giving students such a list, nor we do not want or expect students to memorize any list. Students should come to understand NOS content by addressing their prior conceptions regarding science and then apply this valid appreciation of science and its processes in decision-making.

Worldwide, there are countless documents (curriculum frameworks, objectives, standards) designed to guide curriculum development by providing goals for instruction, yet none advocate memorization as a way of teaching and learning. The consensus NOS learning goals are not even designed for students, but rather for teachers, curriculum developers, and assessment experts. We want students to learn NOS principles in such a way that they can take responsible action informed by understanding, not memorization.

Consider the widely repeated but inaccurate statement, "Maybe I'll believe in evolution in the future; right now, it's *just* a theory." That "just a theory" phrase makes no sense to those who understand the "theory/law" distinction included in many of the NOS consensus recommendations. If a student recognizes that the mechanism for evolution is the *theory* of evolution by natural selection and that theories are well-tested and widely accepted explanations of how a phenomenon operates, they should reject the inappropriateness of the "just a theory" remark. Simple memorization may result in declarative knowledge, but the true understanding comes when such knowledge is appropriately translated into procedural action such as by those who would push back against the banality of "just a theory" with respect to evolution.

Here is where a distinction between declarative and procedural knowledge looms large in the discussion. Ford (2008) further suggests that "knowledge of" (declarative knowledge) and "knowledge of how to" (procedural knowledge) may not even be two sides of the same coin. He implies that those "who have a grasp of practice may or may not be able to translate this knowing" into equal success on various kinds of measures (p. 173). This is an excellent point. Perhaps scientists, who know how to "do" science, might perform poorly on a test of declarative knowledge of NOS. In addition to future work on curriculum development leading to effective ways to teach NOS, we should also concern ourselves with the development of appropriate assessments of NOS with this point in mind.

We know that teachers' understanding about NOS affects their beliefs about teaching it (Waters-Adams 2006), but we also know that teachers do not hold clear ideas about NOS and, therefore, are often reluctant to include NOS in their classrooms (Morrison et al. 2009). Only when teachers understand NOS themselves are they likely to embrace it (Sarieddine and BouJaoude 2014), but they need to know what NOS aspects to teach and what NOS aspects they must understand. Fortunately, that situation is clear, and the consensus set of goals has helped to provide that clarity.

2.5 Conclusions

The debate regarding the consensus view of NOS has been enlightening because none of us who support NOS instruction and encourage next steps want to believe that we are done with this conversation. We should always be reconsidering and ultimately updating recommendations for any science content, particularly in the light of new information – particularly about how science functions. However, we do feel a sense of frustration because it feels as if those who criticize consensus must be suspicious of any recommendations for science content, but it is difficult to know how to respond. Many the issues that some believe we should include in NOS for science class, such as the inevitable debates among philosophers about some element of science practice, may be fascinating and important to the philosophy of science community. However, given the extraordinary content already in the school science experience are simply beyond the time available. With NOS and all other science content, once students learn about issues upon which there is widespread agreement and support, taught in engaging ways by teachers who hint at the landscape beyond, they will have a shared foundation necessary to make use of their NOS knowledge and *then* explore more deeply. We must shake off the "paralysis of perfection." We really do know what main NOS topics should be included in science class that, in turn, will provide a solid foundation for science teaching and inform students in their future lives as citizens in a science-rich world.

References

Achieve, Inc. (2013). *Next generation science standards*. Retrieved from Next Generation Science Standards: http://nextgenscience.org/

Chevallard, Y. (1989). *On didactive transposition theory: Some introductory notes*. Paper presented at the international symposium on selected domains of research and development in mathematics education, proceedings (51–61). Slovakia: Bratislava. http://yves.chevallard.free.fr/spip/article.php3?id_article=122.

Driver, R., Leach, J., Millar, R., & Scott, P. (1996). *Young peoples' images of science*. Buckingham: Open University Press.

Duschl, R. A., & Grandy, R. (2012). Two views about explicitly teaching nature of science. *Science & Education, 22*, 2109–2139.

Erduran, S., & Dagher, Z. R. (2014). *Reconceptualizing the nature of science for science education*. Dordrecht: Springer.

Ford, M. (2008). "Grasp of practice" as a reasoning resource for inquiry and nature of science understanding. *Science & Education, 17*, 147–177.

Hodson, D. (2014). Nature of science in the science curriculum: Origin, development, implications and shifting emphases. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 911–970). Boston: Springer Publishers.

Hodson, D., & Wong, S. L. (2014). From the horse's mouth: Why scientists' views are crucial to nature of science understanding. *International Journal of Science Education, 36*, 2639–2665.

Irzik, G., & Nola, R. (2011). A family resemblance approach to the nature of science for science education. *Science & Education, 20*, 591–607.

Kampourakis, K. (2016). The “general aspects” conceptualization as a pragmatic and effective means of introducing students to the nature of science. *Journal of Research in Science Teaching, 53*, 667–682.

Kötter, M., & Hammann, M. (2017). Controversy as a blind spot in teaching nature of science. *Science & Education, 26*, 451–482.

Lange, M. (2009). *Laws and lawmakers: Science, metaphysics and the laws of nature*. Oxford: Oxford University Press.

Morrison, J. A., Raab, F., & Ingram, D. (2009). Factors influencing elementary and secondary teachers’ views on the nature of science. *Journal of Research in Science Teaching, 46*, 384–403.

Samarapungavan, A., Westby, E. L., & Bodner, G. M. (2006). Contextual epistemic development in science: A comparison of chemistry students and research chemists. *Science Education, 90*, 468–495.

Sarieddine, D., & BouJaoude, S. (2014). Influence of teachers’ conceptions of the nature of science on classroom practice. *Eurasia Journal of Mathematics, Science & Technology Education, 10*, 135–151.

Schizas, D., Psillos, D., & Stamou, G. (2016). Nature of science or nature of the sciences? *Science Education, 100*, 706–733.

Southerland, S. A., Johnston, A., & Sowell, S. (2006). Describing teachers’ conceptual ecologies for the nature of science. *Science Education, 90*, 874–906.

van Dijk, E. M. (2011). Portraying real science in science communication. *Science Education, 95*, 1086–1100.

van Dijk, E. M. (2012). Relevant features of science: Values in conservation biology. *Science & Education, 22*, 2141–2156.

Waters, C. K. (1998). Causal regularities in the biological world of contingent distributions. *Biology and Philosophy, 13*, 5–36.

Waters-Adams, S. (2006). The relationship between understanding of the nature of science and practice: The influence of teachers’ beliefs about education, teaching and learning. *International Journal of Science Education, 28*, 919–944.

Wittgenstein, L. (1953/2009). *Philosophical investigations* (Rev. 4th edn.) New York: Wiley-Blackwell.

Chapter 3
Principal Elements of Nature of Science: Informing Science Teaching while Dispelling the Myths

William F. McComas

3.1 Introduction

Although the science education community is united in support for the inclusion of aspects of nature of science (NOS) in the science curriculum, some do not embrace the recommendations offered by proponents of the consensus approach. As discussed in Chap. 2, we feel that these objections may be reasonably addressed. Furthermore, in science and in science education – particularly on matters of curriculum design – consensus is the way to make decisions. We have reached consensus about the traditional science content that is the instructional focus in biology, chemistry, physics, and every other introductory school subject, and there is no reason why shared thinking would fail us now in defining what topics from the history and philosophy of science should be woven into the science curriculum. Consensus building regarding the importance of some NOS elements started years ago with suggestions offered by many of the pioneers in this field. To be sure, some of those early suggestions, such as teaching about the scientific method, have caused problems by misrepresenting the process of science. However, both science and science education are self-correcting enterprises, so the more recent suggestions for NOS content more accurately reflect how science functions, what its philosophical presuppositions are, and even the limits under which science operates.

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_3

3.2 Suppositions and Assertions About NOS Framing This Chapter

Before discussing this set of NOS ideas in detail, it is important to be clear about several issues and misconceptions encountered when encountering any proposals for such content.

3.2.1 NOS Content Described as a Set of Learning Goals Is Offered to Drive Instruction, Not a List to Be Memorized

The NOS recommendations discussed in this chapter are offered as a set of learning objectives but are not a list to be memorized any more than one would want students simply to memorize the names of the parts of the cell without understanding the location, context, and purpose of those parts along with an appreciation of how knowledge of cell parts might be applied to biology knowledge generally. The goal of this book is to advance the conversation of how NOS should be taught and features the views of a variety of scholars offering a variety of approaches to support this goal.

3.2.2 Science Educators Are Not Philosophers of Science

While there are a few science educators who hold degrees in or related to the history and philosophy of science (HPS), most if not all science education experts, with interests in the HPS/NOS area, are not actively contributing to knowledge in the content of these areas. This admission is not a problem or even unusual. As we will see next, educators with expertise in science learning are often called upon to translate content into curricular recommendations.

3.2.3 Science Educators Must Work with Appropriate Experts to Define NOS Learning Goals

The recommendations found throughout this book and particularly those in this chapter are included with reference to what Chevallard (1989) calls “epistemological vigilance” and “didactical transposition.” What this means is that those in science education with expertise in the domain of NOS have studied the history and philosophy of science, and other related areas have now accurately – or vigilantly in his words – interpreted and summarized findings from professionals in these fields. In turn, we have made recommendations for the HPS content that is most appropriate in school science settings. Next, this NOS-related content must be transposed (i.e., transformed) into learning objectives and curriculum models and recommended as teacher content knowledge and assessment goals. Since the advent of science as a school subject at all levels, educators have been engaged in this two-part task.

However, it makes no more sense for historians and philosophers of science to be the sole arbiters of what from their content domain enters the science curriculum as it does for a Nobel Prize-winning physicist to develop a middle-school physical science curriculum only with her colleagues. Expertise is shared by those who create and define knowledge and those who make recommendations about what and how to teach it. With NOS and with all science content, we offer recommendations with vigilance and then propose effective and engaging modes of transmission or transposition. Thus, NOS is a pedagogical construct designed to inform the introductory science curriculum at all levels. Therefore, when making decisions about what to include in school science, it is vital to consider a multitude of issues, including the readiness of students to learn at a given age, how packed the curriculum is with other content, how particular NOS content might be supported by packaging it with other topics, and so on. This does not mean that any conclusions about NOS should be declared final and off limits, but a constant churning is not productive in moving toward NOS inclusion as a curriculum goal.

3.2.4 There Is No One Right Way to Teach About NOS

It seems unnecessary to make this claim, but with the specter of list memorization as constant criticism, it is wise to make this a presupposition in this chapter. There are scores of chapters in this book each of which takes a different position about NOS instruction and that is as it should be. Teachers are the ones best poised to translate the NOS destination into an enjoyable voyage for students. If we consider the views of just two contributors to this book, we note that Clough (in 2007 and in Chap. 15) recommends teaching the NOS elements as questions and Allchin (2011) advocates engaging students in case studies (Allchin et al. 2014) featuring problem-solving opportunities showing science in holistic fashion he calls "knowledge of whole science."

3.2.5 We Expect the Focus of Instruction Is on Teaching About NOS

There can be no reasonable expectation that NOS learners in introductory school science experiences are going to become philosophers of science any more than we would expect all science learners to become scientists, and this expectation logically would impact the goals of NOS instruction. We do not want to "dumb down" or mispresent issues of NOS. But, when Kötter and Hammann (2017) remind us "there is a consensus in philosophy education that it is essential to teach knowledge about different positions and aspects – rather than a specific view…" (p. 461), this is a prime example of unshared expectations and a potential source of conflict.

School science is not a philosophy class; rather the goal is to teach students about the findings from the history, sociology, and philosophy of science. This is just as true for aspects of NOS as it is for aspects of chemistry. Learners are engaged in learning about chemistry; they are not chemists and do not learn all the content of chemistry by active inquiry as chemists do. This is true with philosophy too. When students major in the philosophy of science at the university level, they are engaged in *doing* philosophy of science and ultimately contributing to it. This is not be taken as any objection to having students think philosophically, but the goal of NOS in school is for learners to come to understand what we already know about how science works. If some want to teach this in a conflict-driven discovery fashion, that is fine but is not particularly efficient given the time available, the capabilities of students, and the overall goals of NOS instruction.

3.2.6 Science Education Is Self-Correcting

If some important aspects of NOS are missing from any proposed set of pedagogical recommendations, we can reopen the conversation about the inclusion of any omissions. If we make recommendations that advocate for factually inaccurate content, NOS included, we look forward to collaboration with content experts to assist in correcting such errors.

3.3 The Development of a Consensus View of NOS for School Purposes: An Introduction

We know that NOS is complex and not a single entity and contains some relatively complex sub-elements. It is very likely that someone could have robust understanding of some of the sub-elements of NOS (called here key NOS aspects) and struggle with others. It has been useful for decades to use the "nature of science" as a quick reference, but there are a very large number of elements that comprise a full understanding of NOS, and some choices must be made with respect to which of those elements ought to be part of the school science curriculum.

Since the advent of advocacy for the inclusion of NOS in the science curriculum, many proposals have been offered for what elements of NOS we should teach. Reviewing all suggestions would both be beyond the scope of this chapter and could confuse the issue since our view of the nature of science has changed through time and older views may no longer be valid. However, if we restrict this review to the "modern" period, we would revisit the pioneering works of Michael Martin (1972) and James Robinson (1968, 1969). We might even deconstruct many of the earlier NOS assessment tools and work backward to gain perspectives regarding what those at the time believed that students should know about NOS issues.

Perhaps one of the most useful and complete sets of NOS recommendations appeared as part of *Project 2061* (AAAS 1989) later codified in the remarkable two-volume set of *Atlases of Science Literacy* (AAAS 2001, 2007). These atlases provide very useful "road maps" of when and where elements of recommended science content, including NOS, should be taught in grade K-12 settings based on research of misconceptions and learner readiness. Detailed presentations on evidence and reasoning, avoiding bias, the nature of the scientific community, and relationship of science and society are among the topics addressed. The issue of NOS learner readiness and learning progressions is discussed in more detail in Chap. 4 of this book.

In a study comparing various suggestions made in the past few decades to describe elements of NOS that should be included in school science, Al-Shamrani (2008) found much overlap. Through the contributions of AAAS (1989, 2001, 2007), Lederman (1992, 1998), Lederman and Lederman (2004), McComas (1998, 2004, 2008), Osborne et al. (2003), and many others, there has emerged a robust set of elements, with some variation. The *Next Generation Science Standards* (Achieve 2013) – the major science standards document in the USA – has incorporated many of the shared notions that define NOS for instructional purposes. Therefore, it would be comforting to think that, at some level, we have decided on the focus within NOS that is best suited to guide classroom science instruction and related science teacher preparation. What has resulted from this work may be called the "key NOS aspects," "general NOS aspects," or a "NOS consensus view." Frankly, I would accept even the label "a pragmatic consensus views of NOS for science teaching and learning" to avoid any misrepresentation of the purpose of these recommendations. This certainly will not catch on because it results in an unwieldy acronym.

With both NOS and traditional science content domains, decisions must be made about what aspects to include and at what level or depth and complexity. As mentioned, there are many overlapping proposals for what elements of NOS should inform the science curriculum, but how could there be a method that would guarantee that this content is properly represented beyond the consensus that seems to have been achieved? We will continue to grapple with this reality and argue for inclusion and exclusion based on our knowledge of the potential NOS elements, our professional experiences with learners (i.e., what might they find interesting, what can they understand at particular age levels), the goals we hold for science instruction, an appreciation for teachers' abilities, the time constrains inherent in school, and some judgments regarding the utility of NOS knowledge in society. Even as the quest to produce shared recommendations for NOS in school science continues, it seems reasonable to conclude that students must have the opportunity to understand how knowledge is generated in the discipline called science. It is nature of science that can provide such an opportunity for understanding.

3.4 A Proposal for Key Aspects of NOS Recommended for Inclusion in the Science Curriculum

The set of recommendations for NOS content included in Fig. 3.1 reflects many of the recommendations widely offered but is unique in that related NOS elements are clustered into three bigger domains labeled the *tools and products of science*, *the human elements of science*, and *science knowledge and its limits*. This proposal had its roots in the suggestions offered by others and original research that involved a review of a variety of recent books written for the general public by professionals in the HPS community (McComas 2008). There was a surprising degree of agreement on what the most important aspects of the philosophy of science should be at an introductory level. The veracity of this summary could be checked every few decades as I did recently by examining a new book by philosopher of science Steven French (2016) with content that neatly parallels the recommendations for NOS content featured here.

The section that follows features a detailed discussion of all nine of the key NOS aspects along with mention of various misconceptions linked to each. Before proceeding, it will be useful to talk briefly about why this set of NOS elements is reasonable.

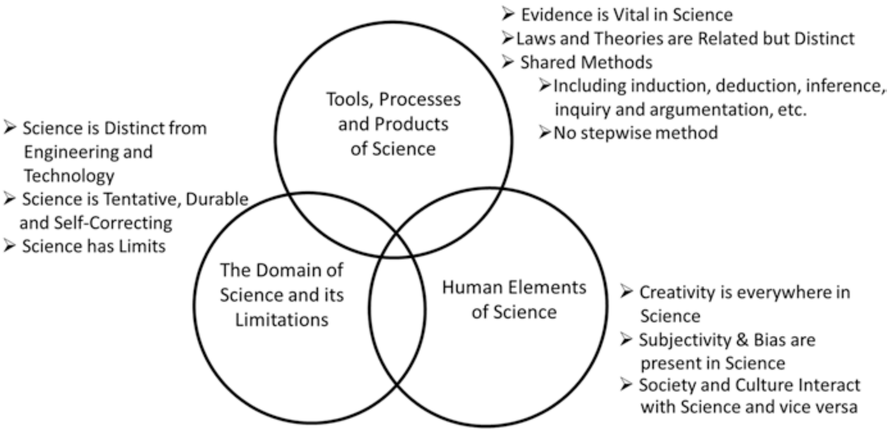

Fig. 3.1 The nine major sub-elements or key NOS aspects often recommended for inclusion in science instruction, arranged in three related clusters. (Modified from McComas (2008) and reflected in the US *Next Generation Science Standards* Achieve (2013)) A complete view of NOS lies at the intersection of these three domains and is achieved when learners have robust understanding of all nine elements

3.4.1 Why Recommend These Elements of NOS for Science Instruction?

Of course, the major reason why these elements are recommended as the foundation for NOS teaching and learning is that they are the ones most frequently mentioned by science educators. Furthermore, these elements function across the science disciplines even if there are some interesting differences as discussed in the case of laws (or "invariant generalizations" for those who reject referring to certain biological generalizations as laws) and theories in biology. Also, this list is short enough that it is not a burden on the science curriculum. In fact, one of the best ways to teach about nature of science is to weave it in to the traditional science content using that content to exemplify the aspects of NOS. Finally, these aspects are understandable to teachers and students at various levels. It is vital to remember that any recommendation for NOS content in the science curriculum represents an introduction to how science functions rather than a graduate-level treatment for the education of future philosophers of science.

3.5 Discussion and Description of Recommended Key NOS Aspects

As pointed out in the previous chapter, we must stop arguing about what might be a perfect list of NOS elements for school purposes and cease the unproductive conversation that there are not common elements linking the sciences. This chapter takes the position that we do possess strong rationales for the consensus view and embraces the recommendation attributed to both Voltaire and Confucius that we *not allow the perfect be the enemy of the good*. Therefore, it is better that science learners have some familiarity with important aspects of NOS than to have ill-informed or missing knowledge as is often the typical situation. No matter if NOS learning objectives are stated in lists, objectives, or questions, these are sophisticated ideas none of which should be satisfactorily communicated to students in some list of definitions to be memorized.

However, it is true that because of the complex and contextualized nature of these NOS elements we must attend to Matthew's (2014, p. 394) concern "that at critical points, there is ambiguity that mitigates the usefulness of items on the [consensus] list as curriculum objectives, assessment criteria and goals of science teacher education courses." This real concern can only be overcome with precise descriptions, focused education opportunities for science instructors, and clearly written NOS standards. Just as Matthews offered in his recent book, this chapter provides succinct descriptions of each of the key NOS ideas in Fig. 3.1 to remove as much potential ambiguity as possible.

Readers must realize that there are substantial "size" differences among these nine key NOS aspects. Some key NOS aspects, such as the role of evidence in science, are relatively discrete and easy to describe, but others, such as the discussion of scientific methods, are much more involved. This difference in the complexity demanded by a discussion of the key NOS aspects proposed here has resulted in a lengthy treatment of some and not of others. Teachers will rightly assume that sharing some of these key aspects will be easier and require less time than doing so with others. Finally, in this section, there will be discussion of each of the key aspects and a discussion of misconceptions regarding each NOS aspect. This chapter adopts and expands on the "myth" approach used in previous publications (McComas 1996, 1998, 2004, 2015, 2017).

3.6 The Tools and Products of Science

The key elements of NOS in this cluster are related because they are required of science (evidence and specific shared techniques) or are produced (laws and theories) using scientific methodology. The necessary role of evidence in science is clear even to young learners, while the lack of a stepwise method and the distinction between laws and theories is a source of confusion to many that results in a variety of misconceptions.

3.6.1 Evidence in the Practice of Science

A fundamental requirement of science is that evidence must exist both to inspire scientific investigation initially and to support scientific conclusions. This interplay between evidence, investigation, and conclusion is dynamic. One way that science works is when evidence in the form of data, facts, inferences (discussed in a later section), and even anomalies present themselves in ways that provoke curiosity causing scientists to look more deeply into phenomenon. As scientists engage in deeper investigations, more evidence is generated through experiments and observations which coalesces into conclusions regarding that phenomenon.

Another way that evidence plays a role in science is when ideas are proposed (usually themselves based on other lines of evidentiary support) by theoreticians which then encourage other scientists to validate those proposed ideas. When Einstein offered his view from thought experiments that light passing near a massive object, such as a star, would bend slightly, the scientific community rose to the challenge during the 1919 eclipse and demonstrated the predicted effect with evidence.

As with many NOS notions, the role of evidence in science is not quite as simple as it seems. As students make the transition from an absolutist view of the nature of evidence that they encounter in their personal lives (evidence that they can "see and hold"), they might enjoy learning about interesting nuanced positions. Consider the example of the evidence for quarks. There are six subatomic entities called quarks, each with a fractional charge. Assemblages of these quarks, in turn, comprise larger particles called hadrons (protons and neutrons are kinds of hadrons). Physicists are almost universally "sure" that quarks exist, but these can never be observed directly because of the issue of "color confinement." Quarks are thought to have a property called color which acts like a charge whose attractive force binds them together. For this reason, one never sees an individual quark. Therefore, strong support for the reality of quarks of different "colors" comes from indirect or perhaps inferential evidence provided by predictions based on the examination of hadrons (Han 1999). The evidence here, which is well accepted by the scientific community, is decidedly less concrete and direct that many would typically envision, but it is evidence nonetheless.

Young children quickly recognize that direct evidence (date or facts) is required to support personal conclusions, while older children accept that inferential evidence too is also quite valuable and valid. Therefore, this key NOS element may be among the easiest to teach, but it is vital to do so. It is regrettable that many adults currently seem not to be able to distinguish between credible and fanciful truth claims perhaps because of what should could as evidence.

Targeted Misconception Scientific evidence is not a "matter of opinion" such that even widely accepted facts can be ignored just as one might discount a personal view with which an individual disagrees.

3.6.2 Laws and Theories Are Equally Important but Distinct Kinds of Knowledge

There is a general belief that with increased evidence, there is a developmental sequence through which scientific ideas pass on their way to final acceptance (Fig. 3.2) as mature laws. The implication is that hypotheses and theories are less secure and therefore less credible than laws. As an example, this confusion is revealed whenever someone says that evolution is "just a theory."

Entire books have been written about the distinction and relationship between theories and laws, so anything said here may be dismissed as incomplete. However, we trust readers will forgive this since the discussion here is intended as an introduction. With that said, theories and laws are very different kinds of knowledge. Laws are generalizations, principles, or patterns in nature, and theories are the explanations of those generalizations with some appending the notion that laws are discovered while theories are invented (Rhodes and Schaible 1989; Horner and Rubba 1979; Campbell 1953; McComas 2003). Of course, there is a relationship between laws and theories, but it is not the case that one simply becomes the other – no matter how much empirical evidence is amassed.

Dunbar (1995) addresses the distinction by referring to laws as "cookbook science" and the explanations as "theoretical science." He cites multiple examples of the kind of science practiced by traditional peoples as "cookbook" because members

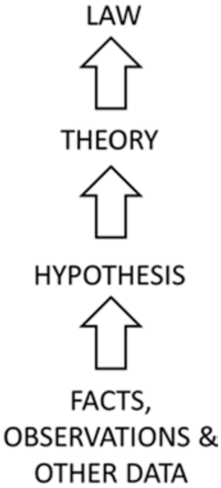

Fig. 3.2 Illustration of the false hierarchical relationship between facts, hypotheses, theories, and laws. Note: Please do not show this to students or you may inadvertently promote this myth to students

of those societies can apply the rules after recognizing patterns in nature, even if they do not understand why nature operates in the way that it does. In many cases, it is enough that the rules work. It has been said that an indigenous group might be negatively impacted if moved even a few hundred kilometers because the “rules” of nature (i.e., when to plant and harvest) may not function as they were known to do previously. Certainly, humans are adaptable and can reason and may quickly learn the “rules” of their new location or even adjust to changes in their current setting. However, the basic idea is valid that there is a distinction between a trial and error adjustment to changed circumstances and an alteration in practices based on a more scientific understanding of the world.

Even in highly sophisticated settings, “cookbook science” may be practiced because it can be quite useful. For example, Newton described the relationship of mass and distance to gravitational attraction between objects with such precision that we can use the law of gravity to plan space flights. During the Apollo 8 mission, astronaut Bill Anders responded to the question of who was flying the spacecraft by saying, “I think Isaac Newton is doing most of the driving right now” (Chaikin 1994, p. 127). To those with knowledge of the history of science, his response was understood to mean that the capsule was simply following the basic laws of physics described by Isaac Newton centuries earlier.

The more interesting issue with respect to gravity is the explanation for why the law operates as it does. Even now, there is no single well-accepted theory of gravity. Some physicists suggest that gravity waves are the correct explanation, while others talk about a kind of gravity particle, but with clear confirmation and consensus lacking, most feel that the theory of gravity still eludes science. Interestingly, Newton addressed the distinction between law and theory with respect to gravity. Although he discovered the law of gravity, he refrained from speculating about its cause. In *Principia*, Newton states “…I have not been able to discover the cause of those properties of gravity from phenomena, and I frame no hypothesis…" "…it is enough that gravity does really exist, and act according to the laws which we have explained…" (Newton 1720/1946, p. 547).

It is true that laws and theories operate somewhat differently in the different sciences – particularly biology – but it should be clear that some things are pattern-like and some offer explanations, and that is the difference between law and theory. For instance, Darwin proposed the mechanism for evolution (i.e., the theory of evolution by natural selection), but he did not discover the idea that populations of organisms change through time. That is evolution itself and has lawlike character even if the predictions with such a law will be less secure than those to be made by the application of Boyle's law in the physical sciences.

Related Misconception There is a widespread belief that theories are a sort of guess, and with time and evidence, they mature into laws. This is untrue. Theories and laws are important and related kinds of knowledge, but one does not become the other.

Having mentioned the faulty lineage from theory to law, we should spend a moment talking about the term hypothesis. This word has taken on an almost mantra-like life of its own in science class with most students labeling it an "educated guess." If a hypothesis is always an educated guess as students typically assert, the question remains, "an educated guess about what?" The best answer for this question must be that, without a clear view of the context in which the term is used, it is impossible to tell; there are at least three distinct definitions. For that reason, the term "hypothesis" probably should be abandoned and replaced or at least used with caution. For instance, when Newton said that he framed no hypothesis as to the cause of gravity, he was saying that he had no speculation about an explanation of why the law of gravity operates as it does. In this case, Newton used the term hypothesis to represent an immature theory.

Sonleitner (1989) suggested a solution to the hypothesis problem by simply making things clearer. He proposes that we label tentative or trial laws as *generalizing hypotheses* with provisional theories referred to as *explanatory hypotheses*. What this means is that, with evidence, generalizing hypotheses may become laws and speculative theories might become theories; however, under no circumstances do theories become laws. Finally, when students are asked to propose a hypothesis during a laboratory experience, the term now means a prediction. As for those hypotheses that are really forecasts, perhaps they should simply be called what they are, predictions. I cannot predict if this new nomenclature will replace the potentially confounding term now used, but doing so would increase the level of precision used in science class and avoid much confusion. Even a term like "hypothesis" demands a degree of sophistication that only deep knowledge of NOS possessed by teachers and students can resolve. See Fig. 3.3 for a summary of this situation.

Targeted Misconception The term "hypothesis" means an educated guess, but this is not true. In practice, hypothesis could be a predication, a tentative law, or a tentative theory. With that many potential definitions, perhaps we could do without it altogether.

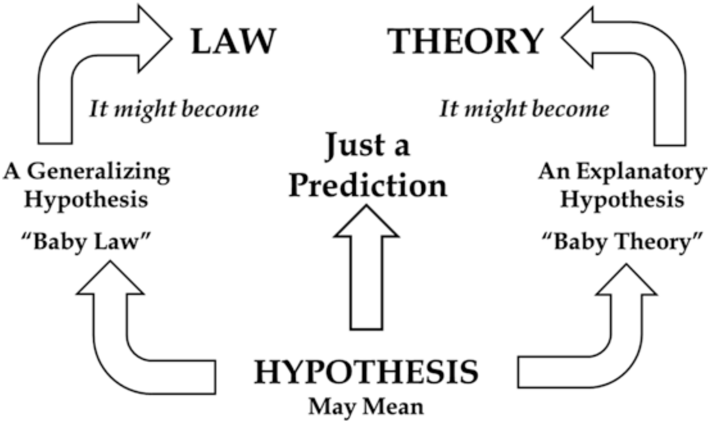

Fig. 3.3 "Family tree" of the term hypotheses, illustrating its multiple definitions and related sources of confusions

3.6.3 There Are Many Shared Methods in Science but No Single Stepwise "Scientific" Method

Discussion of this NOS aspect begins with an apparent contradiction. While there are many shared methods in science, there is no single scientific method. What this means is that there are most certainly generalized techniques that all scientists share that students themselves should practice. However, there is no single step-by-step method (i.e., the so-called scientific method that many science learners are taught that scientists use in all cases).

In this section, we will discuss both issues, shared practices and the lack of a commonly applied and standardized method with some number of fixed steps, and this reality may be confusing if one moves too quickly. Since there are methods, but there is no method, it may be best to discuss the methods that scientists do share before tackling the issue of what they do not.

3.6.3.1 Shared Methods of Science

Of course, there are methods that virtually all scientists would recognize as legitimate scientific practices. Here, we are not talking about procedures and techniques found within a given discipline like titration in chemistry, gene amplification in biology, and the like. No, there are a wide number of activities that scientists universally would find both acceptable and even required including careful record keeping; high ethical standards; the use of logical tools such as deduction, induction, and inference; proposing models; the use of deduction and other considerations like the norms of publishing; the process of grant funding to support research; and other sociocultural aspects of science discussed elsewhere in this chapter. Sober (2015) nicely summarizes this issue as he agrees that there is no single method, but there are most certainly shared methods of reasoning and collective values.

In fact, there have been several curriculum projects which shared the goal of teaching students about the work of scientists by engaging them in the use of scientific methods. One such project from the heyday of US science curriculum development was Science – A Process Approach (S-APA) (AAAS 1967). The authors of S-APA observed and interviewed scientists to define a suite of skills (usually known as "science process skills") that might describe the range of their shared work. These process skills became the focus of instruction. Although the project was somewhat naive in its pedagogical focus, generations of science teachers have come to know at least some of these skills (observation, measuring, defining operationally, etc.) proposed by the project along with other shared processes such as modeling. An initiative in the UK, the *Warwick Process Science Project* (Screen 1986), had similar aims.

A more recent analysis (Peters-Burton and Baynard 2013) found that scientists agree that they share as many as 27 characteristics, a list that is more robust and philosophically grounded but not antithetical to those proposed by S-APA. These characteristics include the use of multiple data sources, making testable assertions, maintaining healthy skepticism, building on past reliable information, the value of reproducing results, looking for counterarguments, changing conclusions with the advent of more information, engaging in multiple experiments, and the importance of peer review, among others. We should also add that argumentation (structured debate) and inquiry (or enquiry as it is called in much of the non-US-English-speaking world) are also tools or "methods" of science. It is with some trepidation that I even mention inquiry because this has been the topic of much debate in science education; is it or is it not part of NOS? There are arguments to be made on both sides. Inquiry is a complex set of actions and philosophical presuppositions that is certainly part of science. Like the other methods of science, it is not exclusive to science but would be recognized as something that scientists do and many other nonscience fact-finding and problem-solving endeavors. For this reason, it is appropriate to see inquiry in the same light as the other tools of science, but I am not prepared to give it the same status as the other NOS recommendations offered here.

So, even as we explore any list of shared methods used by scientists we must remind ourselves that all such methods are used in other professions and in daily life. Even if these methods are not exclusive to science, they are useful in helping to define scientists' practices. It would be foolish to attempt to list all practices *not* used by scientists generally, but "reading" the entrails of a freshly killed chicken to gain insights about the future, using a Ouija board to gain insights about the world, and making judgments based on the position of the stars at the time of one's birth would be on the short list. With no further digression, let us move on to discuss three major shared scientific methods, induction, deduction, and inference, that students should have an opportunity to explore.

Induction, Deduction, and Inference as Shared Methods of Science

One particularly important shared method is represented by the widespread use of the twin logical tools of induction and deduction (Fig. 3.4). All of us, including scientists, collect and interpret empirical evidence through these processes. Induction, for instance, is a technique by which individual pieces of evidence are collected and examined until a law is discovered or a theory is invented. Frances Bacon (1620/1952) first formalized induction as a method in the seventeenth century. In his 1620 book, *Novum Organum*, Bacon advised that facts should be assimilated without bias to reach a conclusion. The method of induction he suggested is in part the principal way by which humans traditionally have produced generalizations that allow predictions. Baconian induction and the related process of deduction (or hypothetico-deductivism) are illustrated in Fig. 3.4. There is something missing in this discussion of induction that will be discussed later, so for now, the process of Baconian induction is most accurately characterized as naive induction. Lawson (2000, p. 482) essentially called such thinking *the* method of science. He states "biology as well as other sciences, is largely hypothetico-deductive in nature…and not at all new to science…."

The proposal of a new generalization (i.e., law) begins through induction as facts are heaped upon other relevant facts. Deduction is useful in checking the validity of a law. For example, if we postulate that all swans are white, we can evaluate that assertion law by predicting that the next swan found will also be white. If it is, the law is supported (but not proved as we will discuss later). Locating even a single actual black swan will seriously damage the credibility of the proposed law.

We conclude this section with a brief discussion of inference, a commonly used method in science and everyday experience. A composition definition shows inference to be a conclusion based on facts, evidence, and data already known to extrapolate to a conclusion (or other data) not seen directly. A favorite example is that of the

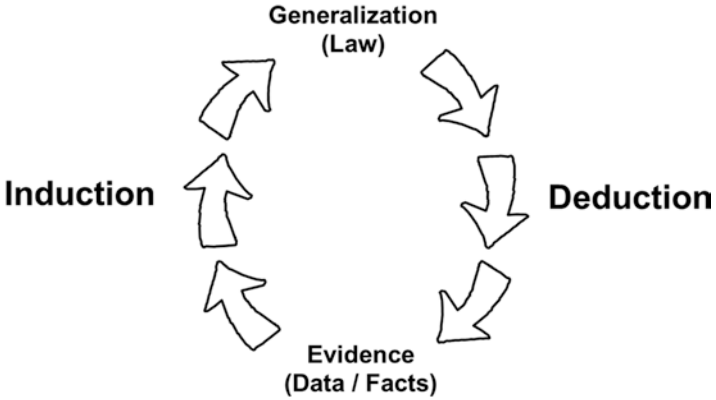

Fig. 3.4 A typical view of Baconian knowledge production. Bacon's view (induction on the left) related to the production of new generalizations and deduction or hypothetico-deductivism (on the right) for the testing of such generalizations. The diagram does not imply that the laws produce new facts but rather that a valid law would permit the accurate prediction of facts not yet known

late-night swimmer. Suppose you have a pool and hear splashing in the middle of the night, but when you investigate, you find nothing in the pool but with wet tracks from some four-footed creature leading away. What might you infer? Logically, you would conclude that some animal was in the pool. You might even measure and photograph the footprints, look in a nature guide, and add to your inference that the animal was a bear. So, with great confidence and perhaps even some enthusiasm, you announce that there was a bear in your pool. Yet you did not see the bear. However, as you recite the evidence, most would agree that your conclusion is reasonable and even likely. This is how inference works. Sure, perhaps someone faked the evidence in the middle of the night for some unknown reason, but such a conclusion seems so unlikely that such a suggestion would be prime fodder for conspiracy mavens.

A few years ago, we in the USA were presented with a televised debate between a supporter of evolution and a creationist. As is often the case with these affairs, there was no winner and there really could not be. The evolution supporter shared vast amount of evidence, much of it in the form of the “hard facts” we often expect of science along with a fair amount of logical inference. Throughout the conversation, the creationist continually said, “but were you there, did you see it?” Any observer should quickly realize that this was not a debate because the two experts did not agree in advance on what should be accepted *as* evidence. If we disallow inferential thinking, many well-established scientific conclusions would cease to exist. The creationist continually stated his belief and acceptance of what was written in the religious literature even though he was not there to see it, but that issue seemed to cause him no problem. Either out of respect or recognizing the mismatch of world views, the creationist was never reminded of this clear logical fallacy. Teaching students about inference as evidence and a shaded method of science is vital. Much conclusion-making in our daily lives is inferential, so even if students forget that they explored this issue in science class, they will long remember the importance of this tool.

3.6.3.2 The Issue and Challenge of the Scientific Method

The notion that a common series of steps is followed by all research scientists must be among the most pervasive myths of science given the appearance of such a list in the introductory chapters of many precollege science texts. The steps listed for the scientific method vary somewhat from text to text but usually include (a) defining the problem, (b) gathering background information, (c) forming a hypothesis, (d) making observations, (e) testing the hypothesis, and (f) drawing conclusions. Some texts also include “communicating results” as the final stage (Fig. 3.5).

The multistep method started innocently enough when Keeslar (1945a, b) prepared a list of the characteristics associated with scientific research. This list included establishing controls, keeping accurate records, and making careful observations and measurements. This is not unlike the process engaged in by the developers of SAPA. This list was refined into a questionnaire and submitted to research scientists for validation. Items that were highly ranked were then put in a logical order and made part of the final list of elements associated with the investigation of

Fig. 3.5 The typical steps associated with the so-called scientific method. The existence of a linear and universal scientific method is one of the most pervasive myths of science in science instruction. As with Fig 3.2 you should not share this diagram with students

scientific problems. In time, the list was reduced from what was an original set of ten to the steps shown in the figure. In the hands of generations of textbook writers, a simple list of characteristics associated with scientific research became a description of how all scientists work. The list is particularly beguiling to teachers because it seems right, is easily taught, looks good on classroom posters, and quickly became the focus of assessment.

Another reason for the widespread belief in a general scientific method may be the way in which results are presented for publication in research journals. The standardized style makes it appear that scientists follow a standard research plan. Medawar (1991) reacted to the common style exhibited by research papers by calling the scientific paper a fraud since the final journal report rarely outlines the actual way in which the problem was investigated. The report is simply a highly stylized but ultimately artificial account of the actual work accomplished. Gone are the days when a scientist could begin a paper by stating as in this fanciful example, “it was a glorious and sunny day when I perchance encountered a highly unusual flower that attracted my eye…” as was often the way Victorian naturalists began a report of discovery.

Those who have studied scientists at work have shown that no stepwise research method is applied universally (Carey 1994; Gibbs and Lawson 1992; Chalmers 1990 and Gjertsen 1989). The notion of a single scientific method is so pervasive that many students must be disappointed if they have an opportunity to discover that scientists do not have a framed copy of the steps of the scientific method posted above each laboratory workbench.

One reaction seen among science teachers when talking about the lack of a stepwise method is legitimate argument that the canonical method shown in Fig. 3.5 seems to be useful in approaching problems. This is an excellent point and one that should be briefly discussed. As a problem-solving tool, the canonical or so-called scientific method can be quite useful and, in that regard, should even be recommended. There are shared methods by which knowledge is gained in science, and these methods can and should be used by all problem-solvers. Science is no different from other human endeavors when puzzles are investigated. Fortunately, this is one myth that may eventually be displaced since many newer texts are abandoning or augmenting the list in favor of discussions of *methods* of science. For a more accurate diagram of the process of scientific investigation, readers are encouraged to consult Reiff-Cox in Chap. 6, who discusses her work on the inquiry wheel.

Targeted Misconception Many believe that there is a general stepwise scientific method that all scientists use, but this is not the case. Although there are many shared methods in science (such as induction, deduction and inference), there is no standard step-by-step method that all scientists use to explore nature.

3.7 There Are Human Elements in Science

The issues found in this cluster of NOS elements are related because they all pertain to the reality that humans do science. That may seem like a self-evident notion, but because humans engage in science, we must be concerned with human strengths, frailties, and associations. We will begin by discussing the vital role played by creativity in science, move on to the issue of subjectivity, and conclude with sociocultural links between scientists and between science and the rest of the world.

Please note that some unpacking is necessary when considering how the label "human elements" is applied. NOS recommendations here may relate most strongly to the work of individuals (a psychological frame), while others are more applicable to scientists interacting in groups and/or with society at large (a sociological perspective). The notions of creativity and subjectivity, discussed in this section, might logically be more psychological, while the sociocultural elements of science likely operate more sociologically. However, having said this, a case could be made that both psychological and sociological impacts function in all three sub-elements of this domain, the human elements of science.

3.7.1 Creativity Plays a Significant Role in Science

We accept that no single guaranteed method of science can account for the outstanding success of science. We do realize that induction, the collection, and interpretation of evidence (usually in the form of relevant facts) providing the raw materials for laws and theories, is at the foundation of most scientific endeavors. However, this suggests a paradox. If induction itself is not a guaranteed method for arriving at conclusions, how do scientists develop useful laws and theories?

Induction makes use of evidence that is collected, analyzed, and examined. Some observers may perceive a pattern in these data and propose a generalization in response, but there is no logical or procedural method by which the pattern is suggested. With a theory, the issue is much the same. Only the creativity of the individual scientist and/or team permits the discovery of laws and the invention of theories. If there truly was a single scientific method, two individuals with the same expertise could review the same facts and likely reach identical conclusions. There is no guarantee of this because the range, nature, and application of creativity is personal, based on prior experiences, and situated with what Kuhn called the paradigm or prevailing framework of science. It is possible to enhance creative thinking, and perhaps that should be an element of the school curriculum, but some folks are simply more creative than others. Figure 3.6 is very similar to the previous illustration of induction and deduction but now includes the somewhat intangible but necessary creative and human spark in the knowledge generation process. It is very likely that two individuals with access to the same facts might reach quite different decisions about what those facts mean based on the prior knowledge and creativity of one.

Creativity and imagination are found throughout science as can be illustrated by countless examples from the history of science (Porterfield 1941). Everything from the identification of a problem worth considering, the specific methods by which that problem may be addressed and, of course, the interpretation of results, has a creative component. Accounts of science are replete too with example of the language of creative such as calling ideas beautiful, economical, imaginative, or even elegant (Glynn 2010). Unfortunately, many common science teaching orientations and methods serve to work against the creative element in science.

Many laboratory exercises in school science are little more than verification activities. The teacher discusses what is going to happen in the laboratory, the manual provides step-by-step directions, and the student is expected to arrive at an expected answer. Not only is this approach the antithesis of the way in which science operates, but such a portrayal must seem dry, clinical, and uninteresting to many students. In her book, *They're Not Dumb, They're Different*, Tobias (1990) argues that many capable and clever students reject science as a career because they

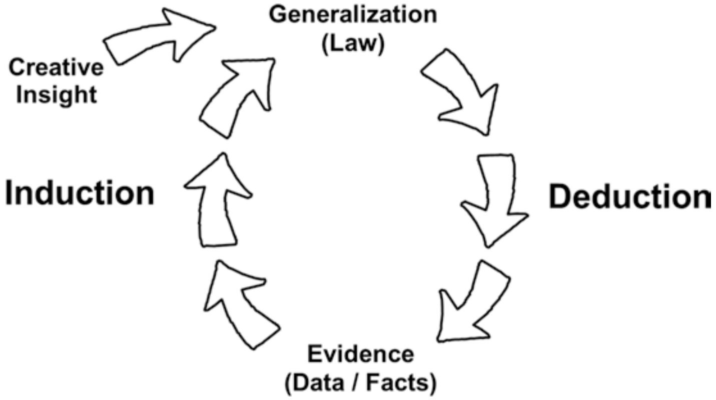

Fig. 3.6 A more accurate illustration of knowledge generation in science. Here, the creative spark or creative leap is included as a necessary element facilitating the move from evidence to generalization

are not given opportunities in school science to see science itself as an exciting and creative pursuit. The moral is that science may be impoverished when students who feel a need for a creative outlet eliminate it as a potential career because of the way it is taught.

Targeted Misconception The myth of the stepwise scientific method has led many to believe that science must be a kind of linear, rote, formulaic pursuit that is nothing like the making of art, for instance. This is not true. There are creative elements all through science including the role of imagination in seeing problems, recognizing patterns, and intuiting solutions.

3.7.2 Science Involves Some Subjectivity

Much of the process of scientific investigation is conducted out of sight, and only the most surprising or potentially useful conclusions are even released to the public. Perhaps for this reason, scientists are likely seen as highly intelligent, savant-like individuals who operate at some superhuman level. The portrayal of scientists on film – particularly from the 1950s – does little to dispel this view. What is much closer to the truth is that scientists are certainly more knowledgeable about what they study than are the rest of us but are human just the same.

What this means is that scientists have the same level of subjectivity (i.e., a lack of total objectivity) as do the rest of us. We all view the world through the lens of our prior experiences in ways that may lead to certain expectations called "theory-laden" observation (Hodson 1986). Scientists, like all observers, hold myriad preconceptions and biases about the way the world operates. These notions, held in the subconscious, affect the ability of everyone to make observations. It is impossible to collect and interpret facts without any bias. Often bias is seen as negative, but that is not necessarily the case. Bias can cause you to miss something because of prior expectations but may just as likely allow the visualization of something that others might miss because the observer is prepared to see it.

There have been countless cases in the history of science in which scientists have failed to include certain results in their final reports. This occurs not because of fraud or deceit but because of the prior knowledge possessed by the individual. Certain facts either were not seen at all or were deemed unimportant due to these prior expectations. This notion, part of the "human dimension of science," discussed in detail in Chap. 6, is not widely understood nor it is widely discussed in science class. Therefore, the challenge of subjectivity becomes a worthy key NOS element.

There is one aspect of subjectivity that relates more closely to scientist than to the observer and that is the relationship of theory-based observations to the paradigm. Thomas Kuhn (1970), in his groundbreaking analysis of science through the lens of its history, suggests that scientists work within a research tradition called a paradigm. This research tradition, shared by those working within a given discipline, provides clues to the questions worth investigating, dictates what evidence is admissible, and prescribes the tests and techniques that are reasonable. Although the paradigm provides direction to the research, it may also stifle or limit investigation. Anything that confines the research endeavor necessarily limits objectivity.

While there is no conscious desire on the part of scientists to limit discussion, it is likely that some innovative ideas in science are rejected because of the paradigm issue. When research reports are submitted for publication, other members of the discipline review them. Ideas from outside the paradigm are liable to be eliminated from consideration as crackpot or poor science and thus will not appear in print. It would be misleading to conclude even this brief discussion of scientific paradigms in a negative fashion. Although the examples provided do show the contrary aspects associated with paradigm fixity, Kuhn would argue that the blinders created by allegiance to the paradigm help keep scientists on track. Kuhn's review of the history of science demonstrates that paradigms are responsible for far more successes in science than delays.

Examples of scientific ideas that were originally rejected and hence delayed in the widespread acceptance of the scientific community because they fell outside the accepted paradigm include the sun-centered solar system, warm-bloodedness in dinosaurs, the germ theory of disease, the asteroid explanation of the demise of the dinosaurs, and RNA as a carrier of genetic information. These ideas now held as valid scientific conclusions were not universally and quickly embraced by many scientists.

For instance, when the idea of moving continents was first proposed early in this century by Alfred Wegener, it was vigorously rejected. Scientists were simply not ready to embrace a notion so contrary to the traditional teachings of their discipline. Continental drift was finally accepted in the 1960s with the proposal of a mechanism or theory to explain how continental plates move (Hallam 1975 and Menard 1986). This fundamental change in the earth sciences, called a revolution by Kuhn, might have occurred decades earlier had it not been for the strength of the prevailing paradigm.

Ideas that help to fill in the gaps that come from the perspective of the existing research framework typically find their way into print realatively easily. However, if the idea is a significant departure from orthodoxy, is counterintuitive, or comes from someone outside the discipline, its acceptance is by no means quick and easy. As we will see later, science is a self-correcting enterprise so even when innovative ideas are held down by senior members of the scientific community, they will eventually rise. On the other hand, this reluctance among scientist immediately to change established norms is probably a good thing in general at least until the major arguments have been resolved.

This issue of subjectivity has clear implications for science teaching. We do not typically discuss the issue of subjectivity, and to make matters worse, teachers often provide learning experiences without considering students' prior knowledge. In the laboratory, for instance, students are asked to perform activities, make observations, and then form conclusions. There is an expectation that the conclusions formed will be both self-evident and uniform. In other words, teachers anticipate that the data will lead all pupils to the same conclusion. This could only happen if each student had the same prior conceptions and made and evaluated observations using identical schemes. This does not happen in general in science, nor does it occur in the science classroom.

It would be premature to end this section leaving readers with the idea that science is nothing more than a subjective morass. It is reasonable to mention the subjective factor resident within scientists and perhaps even within research teams, but science is a community affair. So, the biases – both pro and con – held by some are not held by others engaged in the same work. Therefore, we should talk about science as an intersubjective enterprise, a very useful concept initially proposed by Logino (1990). Some have co-opted this notion for postmodernist purposes, but that challenge aside, it is a useful way of explaining how the strengths and weaknesses, differential biases, and varying experiences of scientists come together in the final marketplace of ideas to move the work of science toward the most reasonable conclusions. This myth targets individuals and small working groups of scientists; thus, the final form of any scientific idea as embraced by the scientific community is essentially free of bias and subjectivity.

Targeted Misconception There is a dominant misconception that scientists are more objective than the rest of us. Scientists know more than others about whatever they are about to explore, but the issues of prior knowledge and theory-based observation and the notion of the paradigm operate against complete objectivity. However, science as an enterprise makes use of intersubjectivity that tends of cancel out any biases held by individual scientists or research teams, thus minimizing negative impacts of theory-based observation.

3.7.3 There Are Sociocultural Impacts on Science and Vice Versa

This NOS aspect found within the domain of "human elements of science" reminds us that because humans do scientific work and engage with each other in a variety of ways, all scientific work will be impacted by these human interactions.

First, much of science relies on external funding and that funding, in turn, is controlled by governments and private foundations that have their own agendas. One might criticize a government that steps up funding due to a national demand such as war and not be as critical when this funding is increased to fight an insect infestation. However, in both cases, there is a problem to be solved, and basic knowledge will be generated in the process as specific problems are addressed. Very few scientists are free to investigate whatever they find interesting unless such tasks are incredibly inexpensive; almost all rely on external funding. For good or bad, that funding is mediated by some public interest typically reflected in the priorities of those providing the money. One only had to look at the past several federal administrations in the USA to recognize that public interests change at least as perceived by those in power. Much more could be said about this, but for an example, consider that one recent administration in the USA wanted to halt stem cell research and the next one found such research worthy of support. As I write this, the current US administration is skeptical and even derisive of the conclusion that the global climate is warming. Previous leaders reached the opposite conclusion and developed policies to slow global warming based on the same data and scientific conclusions now held as unreliable.

Bell (2004) provides several useful historical examples of the interplay between science and society. He said that cultural influences have:

> the potential to impact what research is done, how scientific findings are reported and received, and even the conclusions of scientific investigations. One need only consider such well-known episodes as the Catholic Church's suppression of Galileo's discovery that the moons of Jupiter revolve around the planet or Darwin‘s 17-year long delay in publishing his theory of natural selection to illustrate the major impact that society can have on science. (p. 436)

There is a second sociological element to science found within science itself; the enterprise of science is basically a community affair. Knowledge generation and validation is run through a people-centered process. When a scientist has a new idea, she first introduces it at a professional meeting, takes note of any criticism and suggestions for improvement, and ultimately submits the work for publication. Other scientists read and comment on the findings and evidence and collectively decides if the article is worthy of publication. This process ideally improves the quality of the scientific work but also acts as a gatekeeper blocking some ideas, and the scientists who contribute them, while accepting others. Students must gain knowledge of the human aspects of science, both in the way that teachers talk about doing science and in the learning experiences they are provided in science classes.

Targeted Misconception Some may believe that scientists generally are permitted to work on problems of interest and, although they do follow their interests and expertise, there are two basic limits on the scientific enterprise. First, scientists need funding; with it, they might work on projects that they were not as personally invested in but for which money is available. At the same time, lack of funding generally blocks work that scientists would like to do personally. Second, even the conclusions offered by scientists must be validated (i.e., endorsed) by others if they are to become part of the shared knowledge base of science.

3.8 The Focus of Science and Its Limitations

This final cluster of NOS elements contains three key aspects that relate to the boundaries of science with implications for its limits. Here, I offer the somewhat controversial position that because of the rules of science (one being the focus on the natural world), there are limits on what science can know, although of the "rules" is that scientific conclusions are ultimately tentative (subject to change) but still long-lasting. The cluster of NOS notions ends with the idea that science is something quite special that is related to other disciplines (i.e., the science vs. engineering/

technology distinction), but science is unique historically and philosophically, and students will be best served if they learn of the distinct nature of science.

3.8.1 Science Is Limited in Its Ability to Answer All Questions

As with others of these NOS aspects, this one is not easily summarized. There would seem to be at least two reasons why we can suggest that there are limits on what science can know. Here, I am not saying that there are things that science does not yet know but that science can never know. The first is the notion that science can provide proof in the classic sense of a definitive answer for all time, and the second relates to areas of inquiry where the methods of science simply do not function.

A common view of science is that, when we know something resulting from the processes of scientific investigation, the idea has been *proved*. However, we must recognize the "problem of induction" whereby it is both impossible to make all observations pertaining to a given situation and illogical to secure all relevant facts for all time, past, present, and future. On a personal level, this problem is of little consequence, but in science, the problem can be significant. Scientists formulate laws and theories that are supposed to hold true in all places and for all time, but the problem of induction makes such a guarantee impossible (Horner and Rubba 1978; Lopushinsky 1993).

Consider the example of the white swans discussed earlier. One could search the world and see only white swans and arrive at the reasonable generalization that "all swans are white." However, the discovery of one black swan has the potential to overturn, or at least result in modifications of, this proposed law of nature. Finding yet another white swan does not prove anything; its discovery simply provides some comfort that the original idea has merit. This is the major issue within science. We can definitively assert that something is not true (i.e., find a black swan). We can never know that we have seen every swan that ever lived and know that they are all white, and thus "prove" the white swan rule. What science does is to investigate a problem to such a degree that finding any contrary evidence is unlikely and therefore decide the case is closed. So, this is a legitimate limit on the ability of science to answer all questions. We will return to this issue when discussing the next key NOS aspect.

The second example of the limits of science is more controversial because it is based on the proposition that there are some areas that simply cannot be explored with the methods of science. Here, we enter the distinction between science, a realm that demands evidence, and religion, a domain of faith where understanding operates without the necessity of evidence. There are also areas arguably beyond the tools of science related to ethical decision-making and even aesthetics. Indeed, entire books have been written exploring what science can legitimately investigate with some proponents of science such as Richard Dawkins who see no limits to the grasp of science. The thoughts offered here can only be an introduction.

It might seem odd to ask the question “why did religion develop?” in the context of suggestions for what students should learn about how science functions, but the two are tied together. Both religion and science are tools that humans have developed to gain answers about the world. We like to think of ourselves as more “advanced” than our forebears, and some – again Dawkins – think that we should have dispensed with religion by now. However, if we consider even the biggest of religious questions such as the nature of a God, science tells us very little. It is useful to engage in a thought experiment and ask what evidence we might collect that God exists and what evidence might we find to demonstrate that God does not.

Suppose one holds a deistic view of God, the notion that there is a supreme being who does not interact with humanity. With such a deity, prayer could have no effect. In such a case, it would be hard to imagine any evidence for or against such a deistic God that could be provided by science. Despite this challenge, some have looked to science to provide evidence nonetheless. Some suggest that the anthropic principle (Barrow and Tipler 1986) provides such evidence. This notion puts forward the premise that there are so many things about the Earth (i.e., oxygen level, distance from the sun, etc.) that it had to be created for humans, and our existence could not possibly be an accident of evolution. Still, given the problem of induction, can science really use even this argument to prove the existence of a metaphysical entity such as God?

There exist a range of other interesting questions well beyond the reality of God it seems that science can make no definitive claim to have resolved. Even when we consider all that science has taught us about fetal development, science cannot tell us whether abortion is ethical or not. Art galleries are filled with a range of genres, individual examples that attract legions of visitors, but can science tell us whether a Vermeer paining is better than a De Kooning? Such puzzles abound, and science can play some role in evaluating them, but it seems clear that science cannot definitively answer all questions. It is reasonable to address this notion with students. Doing so not only shows science in its proper light as one way of understanding the world but also embraces students’ individual experiences and keeps them in the conversation about the role of science rather than encouraging them to question the utility of science as many seem inclined to do in recent times. Thoughtful theologians, ethicists, and scientists have carved out their spheres of influence and expertise and have coexisted with little acrimony. Those who fail to understand the distinction between science and other ways of knowing will continue to confuse the rules, roles, and limitations of these important world views. Asking an interesting question of the wrong experts will result in misunderstanding and increase the potential of wholesale rejection of an entire area of expertise. Finally, we might argue that by discussing the limits of science, teachers help to avoid inadvertently encouraging a scientistic worldview in students. Scientism, of course, is the position that science can answer all the questions of humankind and that we need no other explantory or investigative tools.

Targeted Misconception Some believe that science offers absolute proof and can potentially address all questions, but both views are incorrect. Simply put, there are limits on the range of scientific methods.

3.8.2 Scientific Knowledge Is Tentative and Self-Correcting but Ultimately Durable

The methods of science have been shown to provide humankind's best way to probing the natural world and developing understanding that stands the test of time. In this sense, the facts and conclusions offered by science are valid. However, new tools, techniques, and interpretations may cause us to change our initial views. Science is constantly undergoing fine-tuning with the occasional radical changes that Kuhn (1970) called "revolutions." We have shifted from an Earth-centered to a sun-centered system, from protein as the most likely molecule to code genetic information to DNA, from a stable Earth to continental drift, and countless other such examples.

Therefore, a hallmark of science is that it is subject to revision when additional information is presented and new insightes are offered and evaluated by the scientific community. Although it is highly unlikely that a scientific revolution will occur and only slightly more likely that smaller scientific conclusions might be overturned, we must recognize that science is tentative even as it is durable (i.e., long-lasting). Scientists and nonscientists alike should take comfort in the fact that science is not dogmatic about its conclusions.

However, some, who might like to discredit science, occasionally seize on the issue of tentativeness and translate that to suggest that scientific conclusions are little more than personal opinions. This is not reasonable, but we must be cautioned to talk about science as tentative but durable. Perhaps another way to say that is that scientific conclusions are long-lasting but might change when compelling new evidence and/or insights and interpretations become available. The "bigger" the scientific conclusion, the more likely it is to be valid and the less likely it will be to change even with more evidence. Climate change conclusions represent a very good example of this point. The data generated in support of the conclusion that the average temperature of the Earth is increasing are so vast and shared so widely by scientists that it would be foolish to expect that conclusion to be overturned.

We will end this section by thinking about tentativeness as part of the self-correcting aspect of science, a connection that is frequently ignored. Creationists are quick to criticize the conclusions of science when those conclusions counter their worldview. Often, they will use tentativeness in their criticism in a highly naive way by stating that science has made errors in the past and stating that what we know today could change tomorrow. Yes, both things are true, but only in an extraordinarily limited sense. Consider the situation in which several teeth found in Nebraska early in the 1900s (Gould 1991) were initially thought to come from primitive human. This view was overturned quickly when the teeth were found to be those of an extinct pig. Scientists made both the initial misidentification and the later revision, but those who want to find fault in the methods of science only discuss the error. There are no examples in the creationism literature where this issue is discussed. Science may not be perfect but is a self-correcting enterprise by design. All citizens should recognize this as one of the rules of the game of science.

Targeted Misconception Many consider the results of science to be final, but that is not true. One of the rules of the game of science is that scientific interpretations can change through the self-correcting mechanism built into science itself. The check-and-balance system of science produces useful and potentially long-lasting conclusions (i.e., scientific knowledge is durable), but such knowledge is always subject to change (i.e., scientific knowledge at some degree is always tentative).

3.8.3 Science and Engineering/Technology Are Related but Distinct

It might seem that this key NOS element is less important than the others, and this may be true in a philosophical sense. However, there is abundant evidence that many individuals have such a limited grasp of the rules of science that they see even something like a refrigerator as a scientific achievement. Certainly, there are scientific principles contained with the system that can maintain a cold environment inside a fashionable box that may now be found in almost every kitchen, but those who leveraged basic scientific ideas into a commercial device are engineers and technologists, not scientists.

So, despite the widespread misunderstanding that televisions, rockets, and computers *are* science, one of the hallmarks of science is that it is not necessarily practical, while air conditioners and iPhones certainly are. The pursuit of knowledge for the sake of knowledge alone is called pure science, while its exploitation in the production of a commercial product is applied science or technology facilitated by engineers. Even the knowledge-gaining agenda of scientists vs. the profit agenda of engineers and the companies they work for is a significant distinction that students should appreciate. Many years ago, the sociologist Everett Hughes offered an interesting, irreverent, and strangely accurate way to distinguish scientists from others who work in related fields when he noted that "Scientists, in the purest case, do not have clients. They discover, systematize, and communicate knowledge about some order of phenomena" (1971, p. 360). That is not to say that there are no limits on what scientists might do, as we will see, but does make the case that if a scientist wanted to study Bolivian butterfly migration patterns few would argue, but no engineer ever designed and built a bridge just because she wanted to.

Today, most investigators work on problems that are at least in part directed from outside their laboratories. Scientists may be directed by the funding they receive; that sociocultural aspect should be made clear to students, but ultimately, the quest is for new knowledge. Engineers blend their knowledge of science to solve a technology challenge almost always motivated by financial gain either because of a current contact (i.e., to build a bridge) or future potential (i.e., to produce a better handheld communication tool). Both are mediated by financial pursuits in ways that "pure" science often is not. Yes, science, technology, and engineering are intertwined (certainly engineers apply scientific methods and principles to determine, for instance, the strength of concrete formulations), but each has their own philosophical underpinning and role in society. It is vital that students – particularly those considering careers – recognize these important distinctions.

This would likely be enough to say on this topic, but two things recently have conspired to make this a critical issue of distinction. First, the education world has been inundated by the promise of some forms of STEM education. One version of STEM education demands that students study science, technology, engineering, and mathematics together in one project. On one hand, this holds promise if instruction remains focused on the individual elements of STEM. However, the integrated STEM (more accurately called I-STEM) model seems to be taking hold as the method by which to teach science in elementary schools, and that is a concern. Currently, students arrive in their secondary school science classes with some content knowledge but little vision about the philosophical factors that define science. In the future, we may see that students who have been in I-STEM learning settings understand less science content knowledge than is now the case and possess considerable confusion about how science functions having conflated the structure and function of science with engineering and even technology.

The STEM education movement growing worldwide is presumably a shared quest to produce more workers in the STEM areas. However, in the USA, there is another challenge regarding science and engineering with the release of the Next Generation Science Standards (NGSS) (Achieve 2013). In this document, we find the explicit recommendation that science teachers include engineering in their classes and have provided a chart indicating common "science and engineering practices." This is unfortunate because to the uninitiated, it now might seem that science and engineering are essentially the same since their practices have been melded together using similar language. The common science and engineering practices are said to be one of the three dimensions of science learning that does not even include NOS, a domain relegated to an appendix and a series of footnotes. This is a recipe for disaster with the potential for further misunderstandings about how these two disciplines function as pointed out by Antink-Meyer and Meyer (2016) in their study of teachers.

While on the topic of NGSS, it seems that there are four challenges that emerge when reviewing the engineering recommendations and their potential impact on NOS: (A) science and engineering are not the same in their methods, goals, and underlying philosophical orientation, but NGSS does not make this clear, (B) science teachers are now asked to teach engineering but have not been given more training or time to teach the extra subject, (C) most science teachers are not ready from a pedagogical content knowledge (PCK) perspective to help students understand the distinctions between the two great but separate disciplines of science and engineering, and (D) there is little evidence that students learn the underlying principles of science while engaging in the sorts of project- and problem-based learning advocated by those who support engineering and technology education as a part of science instruction. Society certainly needs both scientists and engineers, but students must recognize the essential differences including philosophies, skills, and motivations that separate these domains.

Targeted Misconception Many individuals see science and engineering as essentially two parts of the same pursuit. There is interplay between these two disciplines, but they are not synonymous. Each makes unique contributions and has distinct roles, history, goals, and an underlying philosophical foundation.

3.9 Concluding Thoughts

These nine key NOS elements are among the most commonly suggested of what might called the "consensus recommendations" for aspects of nature of science that should be included in science classes. These elements and others, as appropriate, should hold equal rank with the more traditional facts and processes that have long defined the science curriculum for decades. For those who disagree with the lists, it will be interesting to see other ways to define science learning goals. For those who disagree with NOS elements on the list, please get to work producing other useful and appropriate conceptualizations of NOS. I have learned from long experience that some will want NOS goals that are more limited, and others will find fault because the nuances inherent within each of these elements have not been explored more fully. There are book-length treatises available on almost all the NOS aspects, so it was impossible to possibly offer summaries to meet all expectations. I take responsibility for the content of this chapter, but all of us contributing to this book agree that it is time to recognize the necessity to include some aspects of NOS in the science classroom. After all, such knowledge lies at the foundation of understanding how science itself functions.

References

Achieve, Inc. (2013). *Next generation science standards*. Retrieved from Next Generation Science Standards: http://nextgenscience.org/

Allchin, D. (2011). Evaluating knowledge of the nature of (whole) science. *Science Education, 95*, 518–542.

Allchin, D., Andersen, H. M., & Nielsen, K. (2014). Complementary approaches to teaching nature of science: Integrating student inquiry, historical cases, and contemporary cases in classroom practice. *Science Education, 98*, 461–486.

Al-Shamrani, S. M. (2008). *Context, accuracy and level of inclusion of nature of science concepts in current high school physics textbooks*. Ph.D. dissertation, University of Arkansas, Fayetteville, AR.

American Association for the Advancement of Science (AAAS). (1967). *Science – A process approach*. New York: Xerox Division, Ginn and Company.

American Association for the Advancement of Science (AAAS). (1989). *Project 2061: Science for all Americans*. Washington: Author.

American Association for the Advancement of Science (AAAS). (2001). *Atlas of science literacy* (Vol. I). Washington: Author.

American Association for the Advancement of Science (AAAS). (2007). *Atlas of science literacy* (Vol. II). Washington, DC: Author.

Antink-Meyer, A., & Meyer, D. (2016). Science teachers' misconceptions in science and engineering distinctions: Reflections on modern research examples. *Journal of Science Teacher Education, 27*, 625–647.

Bacon, F. (1620/1952). The new organon, in R. M. Hutchins, (ed.), *Great books of the western world, Vol. 30. The works of Francis Bacon*, Chicago, Encyclopedia Britannica, Inc., 107-195.

Barrow, J. D., & Tiper, F. J. (1986). *The anthropic cosmological principle*. New York: Oxford University Press.

Bell, R. L. (2004). Perusing Pandora's box: Exploring what, when, and how of the nature of science instruction. In L. Flick & N. Lederman (Eds.), *Scientific inquiry and nature of science* (pp. 427–446). Dordrecht: Kluwer Academic Publishers.

Campbell, N. (1953). *What is science?* (Vol. 6, p. 18). New York: Dover Publications.

Carey, S. S. (1994). *A beginner's guide to scientific method*. Belmont: Wadsworth Publishing Company.

Chaikin, A. (1994). *A man on the Moon: The voyages of the Apollo astronauts*. New York: Viking Press.

Chalmers, A. (1990). *Science and its fabrication*. Minneapolis: University of Minnesota Press.

Chevallard, Y. (1989*). On didactive transposition theory: Some introductory notes*. Paper presented at the international symposium on selected domains of research and development in mathematics education, Proceedings (pp. 51–61). Slovakia: Bratislava. http://yves.chevallard.free.fr/spip/article.php3?id_article=122

Clough, M. P. (2007). Teaching the nature of science to secondary and post-secondary students: Questions rather than tenets. *The Pantaneto Forum, 25*.http://www.pantaneto.co.uk/issue25/clough.htm

Dunbar, R. (1995). *The trouble with science*. Cambridge: Harvard University Press.

French, S. (2016). *Philosophy of science: Key concepts*. London: Bloomsbury.

Gibbs, A., & Lawson, A. E. (1992). The nature of scientific thinking as reflected by the work of biologists and by biology textbooks. *The American Biology Teacher, 54*, 137–152.

Gjertsen, D. (1989). *Science and philosophy past and present*. New York: Penguin Books.

Glynn, I. (2010). *Elegance in science: The beauty of simplicity*. New York: Oxford University Press.

Gould, S. J. (1991). An essay on a pig roast. In *Bully for brontosaurus* (pp. 432–447). New York: W.W Norton.

Hallam, A. (1975). Alfred Wegener and the hypothesis of continental drift. *Scientific American, 2322*, 88–97.

Han, M. Y. (1999). *Quarks and gluons: A century of particle charges*. Singapore: World Scientific Publishing Company.

Hodson, D. (1986). The nature of scientific observation. *School Science Review, 68*, 17–28.

Horner, J. K., & Rubba, P. A. (1978). The myth of absolute truth. *The Science Teacher*, (45), 29–30.

Horner, J. K., & Rubba, P. A. (1979). The laws are mature theories fable. *The Science Teacher, 46*, 31.

Hughes, E. C. (1971). *The sociological eye: Selected papers*. New York: Routledge.

Keeslar, O. (1945a). A survey of research studies dealing with the elements of scientific method. *Science Education, 29*, 212–216.

Keeslar, O. (1945b). The elements of scientific method. *Science Education, 29*, 273–278.

Kötter, M., & Hammann, M. (2017). Controversy as a blind spot in teaching nature of science. *Science & Education, 26*, 451–482.

Kuhn, T. S. (1970). *The structure of scientific revolutions* (2nd ed.). Chicago: University of Chicago Press.

Osborne, J., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. (2003). What "ideas-about-science" should be taught in school science? A Delphi study of the expert community. *Journal of Research in Science Teaching, 40*, 692–720.

Lawson, A. E. (2000). The generality of hypothetico-deductive reasoning: Making scientific thinking explicit. *The American Biology Teacher, 62*(7), 482–495.

Lederman, N. G. (1992). Students' and teachers' conceptions of the nature of science: A review of the research. *Journal of Research in Science Teaching, 29*, 331–359.

Lederman, N. G. (1998). The state of science education: Subject matter without context. *Electronic Journal of Science Education, 3*, 2. http://wolfweb.unr.edu/homepage/jcannon/ejse/lederman.html.

Lederman, N. G., & Lederman, J. S. (2004). Revising instruction to teach nature of science. *The Science Teacher, 71*, 36–39.

Longino, H. E. (1990). *Science as social knowledge: Values and objectivity in scientific inquiry*. Princeton: Princeton University Press.

Lopushinsky, T. (1993). Does science deal in truth? *The Journal of College Science Teaching, 23*, 208.

Matthews, M. R. (Ed.). (2014). *International handbook of research in history, philosophy and science teaching*. Boston: Springer Academic.

Martin, M. R. (1972). *Concepts of science education: A philosophical analysis*. Greenview: Scott Foresman.

McComas, W. F. (1996). Myths of science: Reexamining what we think we know about the nature of science. *School Science and Mathematics, 96*, 10–16.

McComas, W. F. (Ed.). (1998). *The nature of science in science education: Rationales and strategies*. Boston: Springer Academic.

McComas, W. F. (2003). A textbook case: Laws and theories in biology instruction. *International Journal of Science and Mathematics Education, 1*(2), 1–15.

McComas, W. F. (2004). Keys to teaching the nature of science: Focusing on the nature of science in the science classroom. *The Science Teacher, 71*, 24–27.

McComas, W. F. (2008). Proposals for core nature of science content in popular books on the history and philosophy of science: Lessons for science education. In Y. J. Lee & A. L. Tan (Eds.), *Science education at the Nexus of theory and practice*. Rotterdam: Sense.

McComas, W.F. (2015, Fall–Winter). Revisiting the myths of science: Guiding classroom practice and enlivening classroom conversations. *Connecticut Journal of Science Education*, *52*(1).

McComas, W. F. (2017). Understanding how science work: The nature of science as the foundation for science teaching and learning. *School Science Review, 98*, 71–76.

Medawar, P. B. (1991). Is the scientific paper a fraud? In P. B. Medawar (Ed.), *The threat and the glory* (pp. 228–233). New York: Harper Collins.

Menard, H. W. (1986). *The ocean of truth: A personal history of global tectonics*. Princeton: Princeton University Press.

Newton, I. (1720/1946). *Sir Isaac Newton's mathematical principles of natural philosophy and his system of the world* (A Motte, Trans.). Revised and appendix supplied by F. Cajori, Berkeley, University of California Press.

Peters-Burton, E., & Baynard, L. R. (2013). Network analysis of beliefs about the scientific enterprise: A comparison of scientists, middle school teacher and either grade science students. *International Journal of Science Education, 35*(16), 2801–2837. https://doi.org/10.1080/09500673.2012.662609.

Porterfield, A. L. (1941). *Creative factors in scientific research*. Durham: Duke University Press.

Rhodes, G., & Schaible, R. (1989). Fact, law, and theory, ways of thinking in science and literature. *Journal of College Science Teaching, 18*, 228–232 & 288.

Robinson, J. T. (1968). *The nature of science and science teaching*. Belmont: Wadsworth Publishing Company.

Robinson, J. T. (1969). Philosophy of science: Implications for teacher education. *Journal of Research in Science Teaching, 6*, 99–104.

Screen, R. (1986). The Warwick process science project. *School Science Review, 68*(23), 12–16.

Sober, E. (2015). Is the scientific method a myth? *MÈTODE Science Studies Journal, 5*, 195–199.

Sonleitner, F.J. (1989). 'Theories, laws and all that', National Center for Science Education*, Newsletter, 9*, 3–4.

Tobias, S. (1990). *They're not dumb, they're different: Stalking the second tier*. Tucson: The Research Corporation.

Chapter 4
Nature of Science and Classroom Practice: A Review of the Literature with Implications for Effective NOS Instruction

William F. McComas, Michael P. Clough, and Noushin Nouri

4.1 Introduction

This chapter provides an extensive review of the literature related to research-based recommendations for what constitutes accurate and effective nature of science (NOS) instruction including key issues such as, explicitness in instruction, student reflection, and degree of contextualization. Next, we focus on four frequently recommended modes for NOS instruction including use of the history of science, socioscientific issues, argumentation, and inquiry. The review continues with an examination of various in-service professional development approaches for preparing teachers to implement accurate and effective NOS instruction. The chapter concludes with a wide-ranging section reviewing challenges that often interfere with efforts to accurately portray NOS, with a focus on assessment, teachers' views and knowledge, NOS learning readiness and learning progressions, the lack of instructional materials, and the realization that NOS is still not viewed widely as a vital science learning goal.

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_4

4.2 Effective NOS Instruction: Key Characteristics

That teachers must understand NOS to faithfully convey it to students goes without saying. However, possessing an accurate understanding of NOS does not mean that teachers will necessarily value it as an important educational goal or know how to teach it effectively. More than a quarter-century ago, Lederman (1992) wrote that "the most important variables that influence students' beliefs about the nature of science are those specific instructional behaviors, activities, and decisions implemented within the context of a lesson" (p. 351). Thus, determining key characteristics of effective NOS instruction has been a major accomplishment of the intense focus on NOS as a teaching and learning goal in science education. These features fall into three basic categories: (1) explicit (i.e., purposeful) attention to NOS, (2) promoting students' mental engagement with and reflection on NOS, and (3) the role of context in NOS instruction. The research literature has long emphasized that effective NOS instruction is both explicit and reflective. Abd-El-Khalick and Akerson (2009, p. 2163) point out that "the label 'explicit' is curricular in nature while the label 'reflective' has instructional implications," but of course, there are many good reasons to combine the two (Scharmann et al. 2005). "Context" refers to the setting in which NOS instruction takes place (e.g., the extent to which such instruction is connected to science content, the work and words of scientists, and socioscientific issues). While a synergistic relationship exists among these categories, the nature and importance of each is addressed and considered individually in the following paragraphs.

4.2.1 Explicit and Implicit NOS Instruction

That NOS can be taught and learned implicitly appears to make intuitive sense. After all, the kinds of activities students engage in, and the ways science is conveyed in curricular materials and via teachers' language, do convey something about what science is and what scientists are like (Dibbs 1982). However, as Clough (2006) notes:

> An important difference exists between the initial development of ideas that make sense to learners, and later efforts to alter those ideas. Examples abound illustrating how children develop ideas to account for their everyday experiences regarding the natural and social world. These ideas, both correct and incorrect, do not necessarily follow from explicit instruction, but once developed may be highly resistant to change. Students' early ideas regarding the NOS are, at least in part, developed in this same way. Implicit experiences regarding what science is and how it works (e.g. extensive experiences with cookbook laboratory activities, textbooks that report the end products of science without addressing how the knowledge was developed, and media portrayals of science and scientists) certainly play a role in learners' developing conceptions of NOS that become deeply held. Mistaken notions of the NOS developed in this way, just like mistaken ideas regarding natural phenomena, resist later implicit and even many explicit attempts to modify those mistaken views. (p. 467)

Thus, while implicit NOS messages may influence the initial development of some NOS ideas, undoing misconceptions and addressing more nuanced and sophisticated NOS ideas demand explicit instructional efforts. What is often referred to as explicit (i.e., purposeful and overt) NOS instruction seems to have appeared first in Akindehin (1988), who stated that enhancing learners' conceptions of NOS "should be planned for instead of being anticipated as a side effect or secondary product" of engagement with science (p. 73). That is, effective NOS instruction is purposely planned for, and it overtly raises NOS ideas and issues during science instruction. Abd-El-Khalick and Akerson (2004, p. 792) write that the term "explicit" means that "NOS understandings as cognitive instructional outcomes, should be intentionally targeted and planned for in the same manner abstract scientific concepts and theories are." In other words, effective teaching of NOS—just like effective teaching of science content, such as the phases of mitosis, the rock cycle, or Newton's laws of motion—demands that specific instructional objectives are clearly and overtly addressed. Teachers who want students accurately to understand NOS must plan for and implement instruction so that their students are aware that such an understanding is an important outcome of science teaching and learning (Schwartz et al. 2004).

Teachers might purposely plan activities that *could* faithfully communicate some aspects of NOS in an implicit rather than explicit manner but this is difficult. As an example, when students engage in authentic inquiry laboratory work they will encounter important NOS ideas such as multiple research methods, the importance of creative thought, the role of evidence, and many other NOS issues. But will students note these issues? When presenting science content, teachers must carefully use language in a way that reflects an accurate view of NOS. For instance, consider how the term "prove" has very different meanings in everyday language and in a nuanced NOS-related context. Indeed, the precise language of science is often at odds with how the same words are used commonly. And while the laboratory is certainly an excellent context in which to learn about many aspects related to the work of science, evidence indicates that learners, using their existing conceptions regarding science, often do not notice implicit NOS issues, misinterpret NOS issues implied in a learning experience, or even alter the implicit NOS message to fit their preexisting misconceptions (Abd-El-Khalick and Lederman 2000b; Moss et al. 2001; Tao 2003). In science lessons where students know they must focus on learning science content, they will rarely attend to implicit NOS issues. Thus, science educators must emphasize that *NOS is content*, and like any content, teachers should carefully plan NOS instruction and overtly draw students' attention to NOS targeted NOS ideas.

In conclusion, we know that some NOS ideas and issues are simply too nuanced or complex for students to learn accurately on their own, even if such elements are found naturally within a lesson. Conceptual change research has clearly demonstrated that implicit instruction is insufficient for altering preexisting misconceptions, so a more direct focus on NOS is vital.

4.2.2 Reflective NOS Instruction

Explicit NOS instruction, discussed in the prior section, can be misunderstood to mean teaching NOS via lecture or other transmission modes of instruction. However, as we noted, explicit NOS instruction means planning for and implementing instruction directed at desired NOS learning outcomes (Akerson et al. 2000). Reflective NOS instruction, on the other hand, emphasizes that NOS should be taught in a manner that requires students to be mentally engaged and think about and understand NOS ideas and issues rather than merely repeating information. Furthermore, reflective NOS teaching includes "providing students with opportunities to analyze their activities from within a NOS framework, map connections between these activities and those of scientists, and make conclusions about scientific epistemology" (Abd-El-Khalick and Akerson 2004, p. 792).

Reflective NOS instruction is in stark contrast to simple memorization and mere recall. Williams and Rudge (2016, p. 412) emphasize that "*Reflective* refers to students having the opportunity to come to their own conclusions about NOS aspects and not just repeating what the instructor tells them." The emphasis on reflective NOS instruction draws from an understanding of how people learn (Duit and Treagust 2003; Posner et al. 1982; Strike and Posner 1992), acknowledging that learning is an active mental process whereby learners use their prior knowledge to make sense of incoming stimuli. Beane and Apple (1995, pp. 15–16) state that "people acquire knowledge by both studying external sources and engaging in complex activities that require them to construct their own knowledge." In the end, a learner's understanding reflects the connections and meaning he or she makes.

However, students' "own knowledge" that they construct may not be accurate! Prior knowledge can assist or interfere in developing accurate understandings, and students may wrongly make sense of experience. When left to come to their own conclusions, students often come to wrong conclusions. Teachers play a crucial role in accurate sense-making; they assess students' thinking and use that knowledge in making purposeful moves to help them develop accurate understanding (Appleton 1997). Thus, reflective NOS instruction is better conceptualized as teacher practices that encourage students to be mentally engaged and think about NOS and that assist students to *come to more accurate conclusions*. This requires that teachers accurately understand NOS and ask questions that effectively assist students in desired meaning-making. Clough (2011a) and Chap. 15 in this book provide many examples of questions to promote student thinking and decision-making while also shaping more accurate NOS understanding. The following are examples of such questions:

- How does the work of [insert "scientist" or "scientists"] illustrate that data do not tell scientists what to think, but instead they must develop ideas that make sense of data?
- What prior knowledge did you use in developing your laboratory procedure and analyzing your data? How does this illustrate that scientific theories guide

researchers in determining what questions to ask, how to investigate those questions, and how to make sense of data?
- Some think that scientific laws are more certain and valuable than scientific theories. How does what you have learned about gas laws and kinetic molecular theory challenge this common view?

4.2.3 Importance of Context in NOS Instruction

A third aspect of effective NOS instruction is the role of context (Clough 2006). Many scholars have argued that various NOS ideas have important nuances and exceptions that depend on context (Allchin 2011; Clough 2007; Eflin et al. 1999; Elby and Hammer 2001; Erduran and Dagher 2014; Hodson 2008; Matthews 2012; Rudolph 2000). Moreover, students often possess extensive and inaccurate NOS frameworks that may remain unaltered by NOS instruction in some instructional contexts. For instance, consider the use of common "black box activities" (several of which are found in Chap. 13), where students are asked to determine how something works or what is inside a container with its contents hidden from view. Such activities are enjoyable and valuable for introducing and focusing on NOS ideas in concrete and familiar ways that are generally uncomplicated by science content, but students may dismiss these experiences as not being authentic science (Clough 2006). This is evident in having to assist students in understanding how decontextualized NOS activities are like science. Devoid of a clear connection and relevance to science content, these NOS learning experiences are often referred to as "decontextualized" or "noncontextualized."

A second broad context for NOS instruction is associating it with science content. For instance, as noted earlier, teaching science content through inquiry provides many opportunities to raise NOS issues (Herman et al. 2013a). Addressing NOS issues in the context of teaching science content is important for helping students link NOS ideas to scientific knowledge. However, lacking clear and direct connection to the authentic work of scientists (e.g., the plethora of methods they employ, their struggles and disputes in making sense of the same data, their creative insights), such NOS learning experiences can still be seen by students as not representative of the work done in science by scientists. Thus, NOS instruction in this context is referred to by Clough (2006) as moderately contextualized.

A third broad context of NOS instruction uses the authentic efforts and words of scientists as a basis for NOS instruction. This highly contextualized NOS learning situation is important for convincing students that their decontextualized and moderately contextualized NOS learning experiences accurately reflect the actual work of scientists. Highly contextualized NOS instruction includes genuine historical and contemporary episodes of science in action, as well as the words of scientists that faithfully reflect NOS. However, because students' prior notions of NOS are filled with misconceptions, without having first been introduced to NOS in less complex contexts, they will likely miss or misinterpret aspects of NOS in highly contextualized situations.

NOS instruction occurring in each of the three broad contexts has distinctive strengths and limitations, but *together* they play a key role in effective NOS instruction. Effective NOS instruction demands paying attention to all three broad contexts and deliberately scaffolding classroom NOS learning experiences and students' developing NOS understanding, back and forth between contexts (Clough 2006, 2017).

Studies investigating the impact of context have provided mixed results thus far. Using global climate change as context, Bell et al. (2011) conducted a study with 75 preservice elementary teachers in four separate groups featuring implicit or explicit-reflective methods in contextualized and decontextualized settings. Groups engaged in an explicit-reflective teaching method were more successful than implicit groups in gaining an understanding of aspects of NOS and using it in new situations, but no significant differences were attributable to the degree of contextualization. Khishfe and Lederman (2006) also reported no differences regarding NOS understanding when NOS instruction was in the context of global warming for one group and without context for another group. However, in a study of preservice teachers, Bell et al. (2016) reported that "teaching and scaffolding NOS lessons along a context continuum can be effective in eliciting desired changes in preservice teachers' NOS conceptions and instructional intentions" (p. 493). Reflecting on previous views, Bell et al. (2016) provided empirical evidence that:

> highly contextualized instruction may support science-content conceptions and help connect students to science knowledge. Noncontextualized instruction may be more accessible for some teachers and students. Thus, the selection of one over the other may lessen the possible benefits of NOS instruction. A potentially helpful alternative to the either-or approach is NOS instruction along a context continuum, a combination of highly and non-contextualized NOS instruction as well as instruction with degrees of contextualization between the extremes. (p. 498)

Allchin et al. (2014) reported that the preference among teachers in a professional development project was to teach NOS in context, writing that the teachers "wanted their students to acquire a more complex and contextualized understanding of NOS in relation to personal scientific inquiry or contemporary cases" (p. 463). Similarly, Donnelly and Argyle (2011) wrote that some teachers in a professional development program "initially found the decontextualized NOS instruction to be a waste of time" (p. 485) and that instruction regarding theory and laws "may have been successful because it occurred within the context of learning about physical science laws and theories (contextualized)" (p. 487).

These mixed results reflect several issues related to efforts investigating the impact of context on NOS teaching and learning. First, how reliably studies have effectively implemented the scaffolding between contexts (as described by Clough 2006, 2017) is unclear at best. The issue is not which context works or works best. Rather, studies are needed in which NOS instruction efforts address NOS more extensively and consistently in a variety of contexts, with extensive scaffolding between those contexts, comparing this approach to single-context instruction.

Second, NOS assessment instruments used in the previously mentioned studies do not address the nuance and depth of understanding that many seek in NOS teaching and learning. Finally, more studies are needed that assess NOS understanding long after treatments have ended. The arguments for the importance of a variety of contexts in NOS instruction, with extensive scaffolding between those contexts, are based on a desire to promote a deep, accurate understanding of NOS that will inform personal and societal decision-making after formal schooling ends. Perhaps the best way to conclude this section is emphasize that further research is needed to determine the importance of context for achieving these noble ends of NOS instruction.

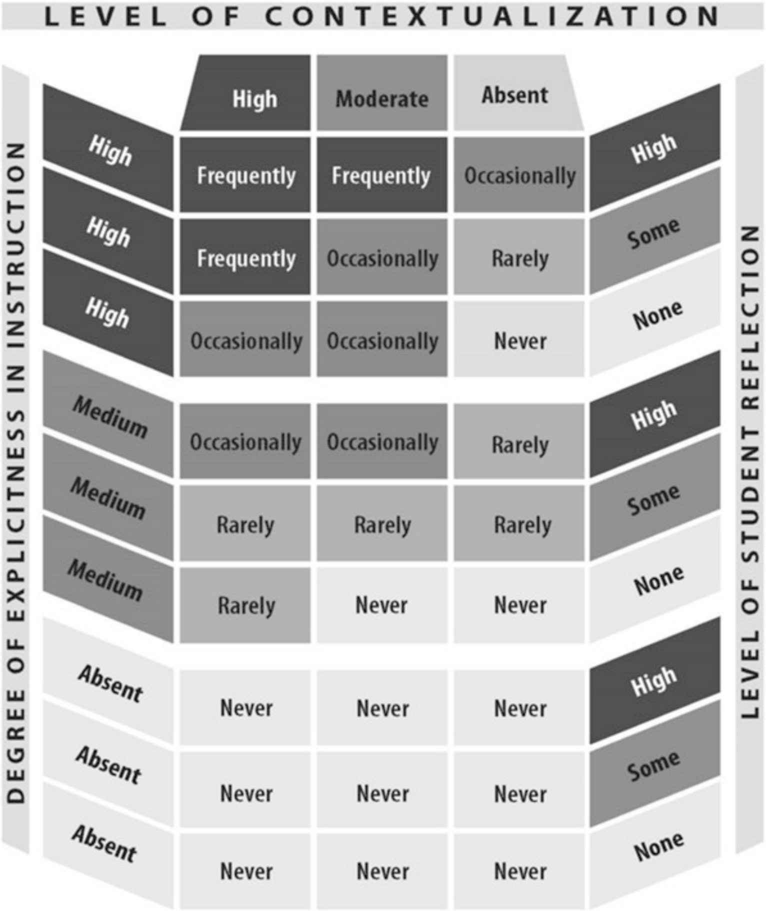
4.2.4 Considering "Explicit," "Reflective," and "Context" in Combination: Implications for Practice

The key characteristics of effective NOS instruction addressed above demand that teachers make informed and thoughtful decisions. Synergistic relationships exist among pedagogical decisions (Clough et al. 2009), and this is clearly a factor in NOS instruction. That is, promoting deep and long-lasting NOS understanding that can be appropriately and flexibly applied in multiple contexts will almost assuredly fail if instruction is not explicit and mentally engaging and does not occur in a variety of contexts, with extensive scaffolding provided to link those contexts. But just how explicit NOS instruction must be, what level of assistance should be provided to students as they wrestle with NOS ideas and issues, how frequently NOS instruction should occur in each of the three broad contexts, and the level of scaffolding that is most optimal cannot be laid out in an algorithm. Teachers should use well-established research recommendations when designing effective NOS instruction. Table 4.1 puts forward recommendations regarding the frequency of NOS instruction where various levels of "explicitness," "reflection," and "context" intersect. Readers may find this useful in guiding decision-making with respect to NOS instruction.

For instance, skilled NOS teachers know that students should have opportunities to mentally engage in reflection particularly with respect to complex or nuanced aspects of NOS. Short, high-quality, interactive presentations (i.e., providing information followed by engaging questions or tasks that require students to express their thinking and reveal their personal understanding) can be very effective vehicles to convey NOS lessons. Effective NOS instruction must be explicit to some extent, and until research provides more conclusive results about the role played by context in NOS instruction, we recommend that instruction occur in all three broad areas (reflection, context, and explicitness), with extensive scaffolding between these domains.

These principal recommendations must be tempered by knowledge of which targeted NOS aspects are most difficult for students to understand and how much assistance learners will require in perceiving, attending to, and finally internalizing

Table 4.1 Recommended frequency of NOS instruction with respect to context, explicitness, and reflection. Contextualization of NOS instruction may occur along a continuum ranging from free of science content ("absent"), linked to the science content being taught ("moderate"), or situated in the work and words of scientists ("high"). The degree of explicitness in NOS instruction is related to how deliberately and clearly the instructor draws students' attention to relevant NOS content in a lesson. The level of student reflection is the extent to which students are encouraged to think about and discuss the underlying NOS elements within a lesson



DEGREE OF EXPLICITNESS IN INSTRUCTION	LEVEL OF CONTEXTUALIZATION			LEVEL OF STUDENT REFLECTION
	High	Moderate	Absent	
High	Frequently	Frequently	Occasionally	High
High	Frequently	Occasionally	Rarely	Some
High	Occasionally	Occasionally	Never	None
Medium	Occasionally	Occasionally	Rarely	High
Medium	Rarely	Rarely	Rarely	Some
Medium	Rarely	Never	Never	None
Absent	Never	Never	Never	High
Absent	Never	Never	Never	Some
Absent	Never	Never	Never	None

and applying NOS. Furthermore, teachers must have knowledge of formal NOS instructional modalities, along with an understanding of the role to be played by metacognitive prompts (see Chap. 9) to foster NOS understanding, a vision of what situations might block the inclusion of NOS in the classroom (Chap. 14), and even an appreciation of how NOS understanding might be assessed (Chap. 22). The primary goal of this book is to illustrate the complexities and possibilities inherent in

NOS instruction and assist in developing instructors who have robust NOS pedagogical content knowledge (PCK) and, ultimately, for NOS to be considered as an important element of classroom science as any traditional science content.

4.3 Instructional Settings That Are Well Suited for Robust NOS Teaching and Learning

Inquiry learning experiences and other instructional activities that require students to engage in decision-making are particularly valuable for creating opportunities for accurate and effective NOS instruction. Such activities engender argumentation and other science practices that are ubiquitous in authentic science research. Some have suggested that, because scientists routinely inquire and argue, these and other scientific practices are the core part of NOS. However, engaging in science practices is not equivalent to understanding NOS. For example, after the launch of Sputnik in 1957, many science curricula in the United States were designed on a framework of inquiry, some of which included NOS elements such as the existence of multiple scientific methods. However, these curricula were often unsuccessful in increasing students' knowledge about NOS, largely because the NOS elements were not discussed explicitly (Lederman 1992; Ramsey and Howe 1969).

Moreover, scientists themselves often possess NOS misconceptions (Kimball 1967; Pomeroy 1993; Schwartz and Lederman 2008). This is not surprising, given that their work is intensely focused on how the natural world works, and few of them stand back and reflect on the philosophical and sociological matters that underpin their work. Einstein and Infeld (1938), Gould (1977), and Medawar (1990) are some noteworthy exceptions, and they and other NOS-sensitive scientists make clear that engaging in science practices is not the same as understanding NOS. This is one of the reasons why we do not see inquiry as NOS per se, but rather as one of the routes to NOS understanding, with the assistance of a well-prepared and knowledgeable instructor.

Thus, we reject the view that merely engaging students in science practices will appreciably improve their NOS understanding, particularly in ways that are relevant to decision-making. That said, some classroom experiences, including those that engage students in science practices, provide exceptional *opportunities* for drawing students' attention to NOS issues and promoting a robust and lasting NOS understanding that can and will be applied in personal and societal decision-making. We present these settings in four broad categories: inquiry science teaching, argumentation, socioscientific issues, and historical and contemporary accounts of science in the making. Figure 4.1 offers an overview of the four broad instructional settings that are often suggested as ideally suited for teaching NOS to promote deep understanding and application. The four broad settings are all valuable for promoting understanding of the three broad aspects of science.

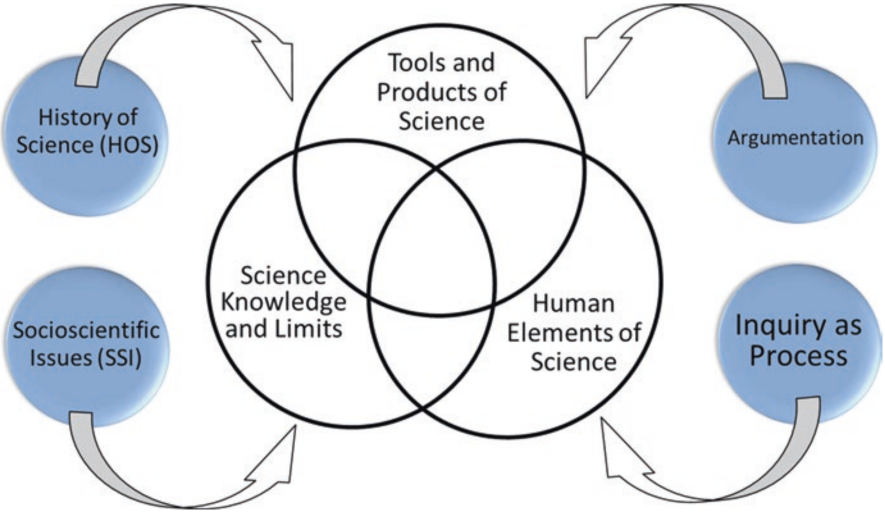


Fig. 4.1 An illustration of four commonly recommended instructional settings, with the implication that each could be used as a foundation for exploring key NOS elements within the three main NOS clusters. (Note: This figure should be seen to suggest that these four settings may be applied to support learning *any* of the nine key NOS aspects)

4.3.1 Inquiry Science Teaching and NOS Instruction

The US *National Science Education Standards* (National Research Council 1996) describes scientific inquiry as:

> the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work. Inquiry also refers to the activities of students in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world. (p. 23)

The *NSTA Preservice Science Standards* (National Science Teachers Association 2012) advocates inquiry instruction generally, stating that teachers should:

> develop lesson plans that include active inquiry lessons where students collect and interpret data using applicable science-specific technology in order to develop concepts [and] understand scientific processes, relationships and natural patterns from empirical experiences. These plans provide for equitable achievement of science literacy for all students. (p. 2)

To help clarify what scientific inquiry entails, the *Next Generation Science Standards* (NGSS Lead States 2013) tells us that teachers are expected to engage their students in:

> practices, such as reasoning carefully about the implications of models and theories; framing questions and hypotheses so that they can be productively investigated; systematically analyzing and integrating data to serve as evidence to evaluate claims; and communicating and critiquing ideas in a scientific community [that] are vital parts of inquiry. (vol. II, pp. 14–15)

Many researchers advocate using a laboratory-based inquiry context for teaching about NOS. For instance, Lederman (2007) stresses the importance of inquiry in saying that "NOS is best taught within a context of scientific inquiry or activities that are reasonable facsimiles of inquiry. That is, inquiry experiences provide students with foundational experiences upon which to reflect about aspects of NOS" (p. 835).

Herman et al. (2013a), summarizing an empirical study of 13 science teachers' NOS instructional practices, wrote that "implementing inquiry laboratories and other activities that require student decision-making appear to be the [general research-based science teaching practices] most important for *creating opportunities* for accurate NOS instruction" (p. 1094). While engaging in inquiry alone does not lead to significant learning about NOS (Sandoval 2003), teaching and learning science through inquiry presents exceptional opportunities for knowledgeable teachers to draw students' attention to NOS issues in a mentally engaging manner. That is, teachers must seize on the many opportunities for NOS instruction that occur in science inquiry experiences and have students "reflect on their experiences from within a conceptual framework that explicates some aspects of NOS" (Abd-El-Khalick and Lederman 2000a, p. 689).

Teaching and learning through inquiry may occur in many settings: immersive projects that students initiate and complete, such as those found as part of science and engineering fairs; typical short-term, laboratory-focused science content investigations (e.g., see Clough 2002); and even short classroom-based activities. Regardless of the setting, teachers must assist students in wrestling with the science content and NOS issues, asking questions that help students develop accurate understanding. For example, Akerson and Donnelly (2008) used contextualized and decontextualized guided and more authentic inquiry to promote K-2 students' views of the creative, tentative, empirical, and subjective nature of science, in addition to observation and inference. NOS teaching strategies included (1) classic NOS activities such as black boxes and "Tricky Tracks," (2) embedding NOS into science content through observations of mealworms followed by design of investigations to determine mealworm preferences, (3) relevant children's literature such as *What Are Scientists?* and *The Skull Alphabet Book*, (4) debriefings and embedded NOS assessments that included asking students to write about their ideas regarding NOS embedded in activities, and (5) guided and student-designed inquiries. Other examples of inquiry-focused activities exist that are ideal for NOS instruction, including those discussed by Akerson et al. (2007), Clark et al. (2000), Clough (2015), Fouad et al. (2015), Gess-Newsome (2002), Lederman, Lederman, and Abd-El-Khalick (see Chap. 17 in this volume), and Price and Perez (2018).

4.3.2 Argumentation and NOS Instruction

Argumentation is concerned with how individuals clarify and justify claims (Driver et al. 2000; Toulmin 1958). Instructionally, argumentation is a teaching strategy that places students in situations where they must compare ideas, taking a position and providing logical and compelling rationales for adopting that position. In doing so, students will be more mentally engaged, comparing their prior knowledge with the new experiences and ideas (Khishfe 2014), and thus more likely to develop new and deeper understandings of content and processes (Osborne 2010).

Developing, expressing, and defending ideas is a central feature of science. Sociologists of scientific knowledge have long emphasized the fundamental role of argumentation in the work of scientists. Sismondo (2004) suggests that "scientists and engineers are always in the position of having to convince their peers and others of the value of their favorite ideas and plans—they are constantly engaged in struggles to gain resources and to promote their views" (p. 9). Thus, not surprisingly, argumentation is often advocated as a viable setting for NOS teaching and learning, a point affirmed through an analysis of the literature by Deng et al. (2011), who write that argumentation has been shown to be effective in increasing students' knowledge of NOS.

Research regarding argumentation and NOS teaching and learning can be divided into studies that address the impact of NOS views on argumentation and those that investigate the influence of argumentation on views of NOS. Research shows a positive influence of NOS on individuals' argumentation skills; students and teachers with more informed NOS understandings will argue with more evidence even if they do not specifically connect their argumentation to NOS (Bell and Linn 2000; McDonald 2010; Sadler et al. 2004; Walker and Zeidler 2004; Zeidler et al. 2002). In a review of the literature, McDonald (2010) concluded, not surprisingly, that students' NOS views do influence their engagement in argument, but that teacher guidance is necessary to help students apply their NOS understanding and to appreciate the relevance of NOS to effective argumentation.

While studies regarding the influence of argumentation on NOS understanding began with work to develop students' argumentation skills, later researchers determined that, because of such efforts, students developed more informed views of NOS (Bell and Linn 2000; Yerrick 2000). McDonald's (2010) review of the argumentation literature related to NOS noted mixed findings regarding the importance of explicit instruction, with some studies hinting that such instruction may not be required in equal measures when argumentation and NOS are linked. He wrote, "These findings suggest that developing learners' NOS views may not require the integration of explicit NOS instruction in scientific contexts where explicit argumentation instruction is provided." But he added that "this assertion is contrary to a large body of research in the field of NOS that supports the notion that explicit NOS instruction is necessary to aid in developing learners' views of NOS." A synergistic relationship may very well exist between argumentation and NOS instruction and should be investigated further to establish the interaction of NOS and argumentation teaching and learning.

4.3.3 Socioscientific Issues and NOS Instruction

Socioscientific issues (SSIs) are defined as science-based social dilemmas (Khishfe 2012) designed for instructional purposes that are "open-ended, ill-structured, debatable problems subject to multiple perspectives and solutions" and often "involve the products and/or the processes of science and create social debate and/or controversy" (Sadler and Zeidler 2005, p. 114). The key in SSI instruction is that the science is well established, but how society should respond to such scientific conclusions is the issue. Sadler et al. (2002) state that such issues consider the role of emotion as a fundamental part of science education in fostering the development of moral and epistemological orientations of students. Discussion of such issues "involves reasoning about causes and consequences and about advantages and disadvantages, or pros and cons, of particular propositions or decision alternatives" (Zohar and Nemet 2002, p. 38).

At some level, both SSIs and STS (science-technology-society) share similarities in their pedagogical approaches, but Zeidler et al. (2005) remind us that STS, as frequently practiced, often (1) is not based in a developmental or sociological framework that actively attends to the learners' psychological maturity and level of knowledge and (2) specifically lacks links to the growth of character, ethics, virtue, and similar considerations (Herman 2018). Proponents of SSI approaches advocate empowering students to consider how science-based issues interact with the moral and virtue elements in their own lives in addition to the natural and social worlds around them.

Much earlier, Wessel (1980) offered three critical distinguishing characteristics of an SSI:

> First, there is always a deep and abiding public interest in its resolution. Second, the information and understanding required in order to come to a rational judgement are extraordinarily complex and difficult to evaluate. Third, a sound final judgment requires the fine tuning and balancing of a number of 'quality of life' value concerns, about which different people may have widely varying attitudes and feelings. (pp. 4–5)

Many SSIs exist, but common classroom examples include fetal tissue implantation, global climate change, and genetically modified food, cloning, and stem cell research. Sadler and Zeidler et al. (2005) point out that "the delineation of socioscientific issues should not imply that those issues not classified as such cannot be mutually influenced by science and society" (p. 114).

Use of SSIs, depending on how extensively science content and the words and work of authentic scientists are included, is an instructional setting that falls somewhere between moderately and highly contextualized NOS instruction. Allchin (2011) argues that addressing aspects of NOS in the context of SSI is indispensable for preparing students to apply such NOS understandings to personal and societal decision-making. For instance, research reveals that decisions people make about SSIs are related to their understanding of NOS (Herman 2015; Kolstø 2001; Sadler et al. 2004; Zeidler et al. 2002). Sadler et al. (2004) showed that "nature of science conceptualizations affect the interpretations of scientific knowledge upon which decisions about socioscientific issues are made" (p. 390).

Using SSIs as a context for NOS instruction has been shown to increase understanding of NOS. In addition, learning NOS in this context often gives learners additional NOS-related evidence with which to justify their decisions. For instance, research shows that students use examples from the context of the controversy to talk about their ideas related to NOS (Sadler et al. 2002, 2004). Comparable results were found by Eastwood et al. (2012), who compared NOS instruction in socioscientific and content-driven situations and found that both were effective in promoting students' NOS understanding.

Matkins and Bell (2007) used the context of global climate change and global warming with explicit-reflective teaching of NOS and showed that elementary teachers achieved a better understanding of both NOS and the related science content. In addition, they were able to apply that understanding in their decision-making about the SSI. Bell et al. (2011) reported that preservice elementary teachers who had explicit-reflective NOS instruction in the context of SSIs related to alternative energy were able to apply targeted NOS views in their justifications.

Wong et al. (2008) and Leung et al. (2015) found that understanding the tentative nature of science was significantly correlated with their experience evaluating health reports from multiple perspectives in news with a socioscientific nature. Schalk (2012) used an SSI-based curriculum in his microbiology course and concluded that students' NOS understanding showed improvement in this context. Khishfe demonstrated that using the socioscientific context of genetically modified food and water fluoridation to explicitly teach NOS was a successful technique for increasing students' knowledge about NOS (Khishfe 2013, 2014, 2015). In her 2012 paper that featured a lesson focused on genetically modified food, Khishfe reported that:

> understanding the NOS aspects in the context of socioscientific issues communicates an authentic view of the socially constructed nature of scientific knowledge. Plus, students are enabled to construct arguments and make decisions in relation to controversial socioscientific issues. (p. 94)

Work by Herman (2015, 2018) further indicates how accurate and contextualized NOS knowledge plays a crucial role in socioscientific decision-making and how that knowledge can be promoted through appropriate SSI instruction. Herman (2015) determined that, among 324 secondary marine science students, those with more accurate and robust perceptions about NOS in relation to global warming science (e.g., the extent that global warming science is valid despite it not proceeding via controlled experiments) were more willing to mitigate global warming across five categories of actions—each requiring varying levels of personal sacrifice.

Finally, Herman (2018) has shown that place-based SSI instruction focused on wolf reintroduction in the Greater Yellowstone Area assisted a large group of secondary students in developing more accurate and contextualized knowledge about NOS aspects such as methodological pluralism, theory and model revision, and the roles that science, technology, and culture play in resolving SSIs. Furthermore, this investigation substantiated the link between NOS views and enacted decision-making in SSI contexts through showing that the students who donated their participant incentives to an environmental organization possessed more accurate and contextualized NOS views than their non-donating counterparts.

Despite the evidence regarding SSI and NOS, some concerns exist that researchers and practitioners must consider. Gayford (2002) points out that teachers face some barriers when including an SSI in instruction. For instance, the controversial nature of the topic is often complex and related to a literature that is difficult to understand. The content involved in exploring the SSI is often not as straightforward compared to the typical way information is presented in science classes. Finally, SSIs often entail important nonscience elements (e.g., ethical and sociocultural considerations) related to viable solutions that teachers may find hard to address. From the students' perspective, the exploration and discussion of SSIs themselves are complex, and they can easily miss or misunderstand NOS issues embedded in those societal issues. Several scholars (e.g., Herman 2015, 2018; Hodson 2009; Zeidler et al. 2013) have indicated that students' diverse characteristics (e.g., sociocultural identity, values, and access to epistemological resources inside and outside of formal learning environments) influence their scientific views and decisions.

These issues and challenges aside, the use of SSIs has a place in a complete and engaging science curriculum. Further, student knowledge of NOS can both add to the conversations regarding such issues and be enhanced by such conversations in much the same way that we have seen with argumentation. To echo other findings about the importance of context, it seems clear that targeting NOS in the context of SSIs is likely crucial for promoting NOS understanding that can be appropriately used in personal and societal decision-making.

4.3.4 History of Science and NOS Instruction

Strong rationales have been given for including the history of science (HOS) in science instruction, a topic discussed elsewhere in this book. Here, we remind readers that HOS instruction has a potential dual benefit: to teach something of the history of science itself and to illustrate important ideas about NOS but only when teachers are poised to make such connections. As McComas (2010) states, HOS:

> can be both a vehicle to convey important lessons about how science functions and a destination in its own right. HOS lessons can humanize the sciences with their inclusion of the personalities who have shaped the direction and products of the scientific enterprise. (p. 39)

Many reasons have been put forward for why HOS is a worthy topic for inclusion in science education, but here, we emphasize that HOS can be leveraged to communicate many important aspects of NOS. This point has been addressed extensively by a variety of researchers in recent years, including Abd-El-Khalick (2005), Abd-El-Khalick and Lederman (2000b), Clough (2006), Hodson (2009), Howe and Rudge (2005), Irwin (2000), Kim and Irving (2010), Kolstø (2008), Lin and Chen (2002), Matthews (1994, 2015), McComas and Kampourakis (2015), Paraskevopoulou and Koliopoulos (2011), and Rudge et al. (2014), among others. These positive comments about the use of HOS are counterbalanced in a cautionary way by others such as Höttecke and Silva (2011) who point out some of the challenges of the history of science-teaching approach.

Allchin (2013) notes that historical background regarding the development and acceptance of science ideas provides context and allows teachers to move from a focus on providing answers to illustrating what he calls the "wonder of unsolved problems" (p. 30). Ultimately, as Adúriz-Bravo and Izquierdo-Aymerich (2009) suggest:

> key nature-of-science ideas can be taught…using the history of science as a meaningful vehicle. It has been shown that selected historical episodes, carefully reconstructed, can work as 'settings' that give meaning to rather abstract epistemological notions and promote their transference to other situations. (p. 1179)

Among the many ways to use HOS to teach NOS ideas (see Chap. 18), two are particularly amenable to classroom science teaching and worth emphasizing. Clough (2011b) reported on a project in which his team developed 30 historical short stories for use in postsecondary introductory astronomy, biology, chemistry, geology, and physics courses. Each story targets the development of fundamental science content while drawing readers' attention to important NOS ideas illustrated in the authentic work and words of scientists. The project website (https://www.storybehindthescience.org) is freely available and provides links to the rationale for the project, six stories for each of the science disciplines noted above, support materials, and research related to the project. Using what might be called the "NOS anecdote approach," McComas and Kampourakis (2015) and Chap. 30 in this volume) who recommend aligning a brief historical account with specific science content and one of the NOS elements targeted for instruction. For instance, a teacher could discuss the NOS element of creativity with Kekule's creative solution to the structure of benzene in chemistry class. This approach makes use of the engaging character of history to teach about NOS while recognizing that teachers feel most comfortable with traditional science content-focused lessons.

The two approaches described above are important because, despite many indications that HOS can be a useful foundation for NOS learning, few science textbooks provide meaningful historical discussions regarding the development of science ideas. As Kindi (2005) reports:

> textbooks…usually include introductory chapters devoted to the history of the corresponding discipline. These chapters mark out great achievements, date great discoveries and honour the heroes of the field. They are not connected to the material that follows and what is said in them is hardly ever taught in class. The most conscientious of the teachers…do not like to spend time on things they consider peripheral and concentrate instead on the teaching of science proper with emphasis laid not so much on theoretical issues but on the solution of problems and exercises. (p. 721)

The focus on facts and principles, as isolated from those who developed them, results in an ahistorical and even distorted picture of science (Abd-El-Khalick et al. 2008; Irez 2009; Pagliarini and Silva 2007) and is far less interesting in this dehumanized presentation.

Moreover, science textbooks that do incorporate HOS too often present what might be called a quasi-historical account of science that distorts NOS (Allchin 2004). They do so by mentioning only the most iconic scientists and provide little more than a picture and summary of their contributions in a very brief, romanticized way. Scientists' contributions are portrayed simplistically and monumentally, inflating genius and ignoring or downplaying difficulties and errors (Allchin 2003). At best, what typically results is a pseudo-history and distortion of NOS that sanitizes the actual practice of science. Textbooks further sanitize the research papers published in science journals, which have already streamlined the actual practice of science. As Medawar (1963) suggests (in his classic paper "Is the Scientific Paper a Fraud?"), what we read in scientific journals is a highly truncated and "sanitized" report of what really transpired in a scientific discovery—resulting in a linear narrative that necessarily omits the interpersonal and political issues, difficulties making sense of data, and inevitable frustrating dead ends that are more reflective of the truth. This will be clear, for instance, if one reads Watson and Crick's (1953) short paper on the structure of DNA appearing in the journal *Nature* and compares it with Watson's (1968) *The Double Helix* published 15 years later. Students will find this later more detailed and personal account of the quest to determine the DNA structure fascinating. See Clough (2015), for a full account of how this book may be used in teaching traditional science content along with HOS and NOS in a secondary school biology class.

In the same way that history of science provides opportunities for teaching NOS, so do contemporary accounts of science. Both can accurately show science in the making, illustrating the difficulties that scientists experience in investigating natural phenomena and making sense of data. While both can be used to exemplify important epistemological and ontological lessons, historical accounts illustrate how difficulties and disputes were resolved, whereas contemporary accounts show how problems and disagreements, still unresolved, are being addressed in efforts to understand phenomena. Historical and contemporary accounts of science both play a key role in convincing students that what they are learning about NOS accurately reflects authentic science (Clough 2006).

4.4 NOS Learning Readiness and NOS Learning Progressions

No matter what NOS learning goals are chosen for instruction and regardless of the instructional orientation such as history or argumentation that might be employed, another important consideration relates to when any such ideas might best enter the curriculum. This decision relates to a range of issues including (1) when particular science content is taught that might be especially conducive for teaching about NOS, (2) what prior conceptions about NOS that students may have at various ages, (3) the NOS interest level of students, (4) the complexity of the NOS aspect in question, and (5) the NOS content and NOS teaching experience of teachers. This section considers the related issues of learner readiness and a NOS learning progression.

As Duschl et al. (2011) write, “Learning progressions are generally viewed…as conjectural or hypothetical model pathways of learning over periods of time that have been empirically validated” (p. 124) and “are seen as de riguere strategies for formulating and developing environments of learning that align curriculum, instruction and assessment” (p. 124). Said in a less technical fashion, learning progressions are the instructional plan that tells educators when and at what level of intricacy some topic should enter the curriculum (with respect to the age/grade level of the learners) and how that topic is further developed in the overall science curriculum.

Student understanding of NOS should grow as learners see applications and explore nuances throughout their school experience. In this way, students’ image of science will become more complex and increasingly more aligned with the authentic picture of real-world work in science as provided by those in the social studies of science working to provide such a description. For instance, an idea like tentativeness in science is extraordinarily complex. If students only were to understand that “conclusions in science can change” without the appropriate context and examples and experience coupled with an understanding of the related NOS notion that “scientific knowledge is durable,” they would have an inappropriate view of the scientific enterprise.

The notion of a spiral curriculum means that students draw on and apply prior knowledge and is a well-validated instruction perspective to ensure that students do not forget what they have already learned by continually reconceptualizing and applying such knowledge while adding new aspects of their understanding. This notion of continually introducing NOS concepts throughout the science curriculum is encouraged from one science class to one in the following year, within a single class or course, and during a single science learning experience (lesson plan or unit). Ideally, NOS would be included where it fits with traditional science content at an appropriate level of complexity for the targeted learners.

The notion of “learning progression” is a straightforward instructional concept but difficult to produce in practice. To propose any such valid progression, one must consider when learners are likely ready for any particular NOS content based on its complexity and what (mis)conceptions learners already possess regarding the targeted content, the developmental level or stage of the learners, what traditional science content that can best support and illustrate the NOS learning goals, what real-world contexts might support NOS learning, the links between some aspects of NOS to others, and how much teachers understand about the NOS goals and what instructional tools teachers have to communicate the content.

Duschl et al. (2011, p. 155) also suggest that effective instructors know the intermediary steps, the "anchor points, stepping stones, lever concepts and linchpins, [linked to] assisted conceptual development that is based on learners' extant knowledge." When all factors are considered, the production of "the" learning progression for any content is likely impossible; it would be better to imagine multiple appropriate learning progressions tied to the target science concept. Of course, there is the possibility that the number of variables precludes the possibility of identifying precise learning progressions.

Proposed learning progressions for any science content, including NOS, must be supported by research findings targeting at least the key issues just mentioned. Classroom teachers' opinions should be assessed in this regard, but this task is complex and must involve data provided by other science education experts as we are reminded by Duschl and Wright (1989). Corcoran et al. (2009) report that even though many science learning progressions have been developed, they are nascent and must be evaluated with respect to their utility (will teachers use them?) and efficacy (do they result in measurable student outcomes in the targeted content?).

4.4.1 Student Readiness: Starting Points for NOS Instruction

An obvious place to begin the developing of the sophisticated learning progressions that might assist educators in communicating NOS in rich and meaningful ways is to determine which of the recommended NOS aspects are conceptually the easiest to understand. In turn, this would lead to recommendations that such aspects be taught to the youngest students. Even this task is complex because learners' prior notions will inevitably interact with new content. Unfortunately, while some misconception studies exist that have revealed student understanding of some NOS aspects, research is not yet complete.

Certainly, some of the recommended NOS elements are likely to be more difficult for younger students because of issues related to cognitive development and students' prior knowledge and experiences. This assumption has been validated by studies showing that students have age-specific misconceptions regarding NOS aspects (Carey and Smith 1993; Driver et al. 1996; and Smith and Wiser 2015). For instance, Akerson et al. (2011a, b) suggest that some of the sociocultural NOS elements may be more difficult for younger learners than are other NOS elements, an expected finding given the complexity of this issue and the assumption that younger learners would not likely encounter related issues in their personal lives.

Sweeney (2010) has made a highly useful contribution to questions about NOS learning with her national survey of K-4 elementary teachers (N = 377). In this

Table 4.2 Percent of K-4 teachers (N = 377) indicating the level of developmental appropriateness for each key NOS element at the kindergarten (students 5–6 years of age) and fourth-grade (students approximately 9–10 years of age) levels

	Kindergarten	Fourth grade
	5–6 years old	9–10 years old
Empiricism in science	97%	100%
Creativity in science	93%	97%
Shared methods	91%	89%
Culture aspects	64%	88%
Tentativeness	56%	82%
Technology vs science	39%	69%
Subjective	37%	67%
Limits of science	21%	51%
Theory/law	12%	31%

Adapted from Sweeney (2010)

study, she provided teachers with descriptions of 12 NOS consensus issues (including the 9 key NOS aspects mentioned frequently in this book) and then asked them about developmental appropriateness at each of the five grade levels. For simplicity, only the K and fourth-grade level results are reported in Table 4.2, but there is a general increasing trend line connecting the two points through Grades 1–3 with some variations.

Teachers report that each key NOS element has a specific developmental appropriateness linked to age/grade level, and almost all the targeted NOS aspects increase in their perceived development appropriateness as grade level increases. An exception to the increase is seen with respect to the idea that “science involves empiricism.” Teachers believe that this issue is highly developmentally appropriate across all grade levels. This is also generally true of “creativity in science.” All other NOS aspects increase in perceived developmental appropriateness. For instance, only 37% of teachers thought that “subjectivity” is appropriate for kindergarten students, but that number increases greatly to 67% for fourth-grade students. The theory/law distinction is seen to be of limited appropriateness for the youngest learners and increases only to 31% for fourth graders. The implications of this important study should be obvious; some NOS ideas are seen by educators as intrinsically more difficult to communicate to students than are others. We would be wise to keep such findings in mind when making recommendations about the introduction of NOS ideas.

The view that students’ developmental level is likely linked to their ability to understand aspects of NOS has been shown to resonate with educators. Deniz and Adibelli (2015) found that lower elementary teachers unsurprisingly made instructional decisions based on what they thought were the most developmentally appropriate NOS elements. This parallels a finding by Hanuscin (2013) who examined critical incidents in the development of elementary preservice teachers’ development of NOS PCK, one of which included forming an understanding of students’ prior knowledge in forming instructional strategies. Demirdöğen et al. (2016)

showed a similar understanding of the importance of knowing student conception among preservice chemistry teachers.

Akerson and a variety of colleagues during the past decades have reported the results of research in early NOS learning for more than a decade providing important insights about NOS learning readiness. For instance, Akerson and Abd-El-Khalick (2003, 2005) found that, with an implicit approach to teaching NOS, fewer than 10% of fourth graders could communicate the role of creativity and imagination in science even after working with a NOS-knowledgeable teacher providing an hour per day of science instruction. An equal number of students had problems understanding that science uses inference and direct observation together to form conclusions. If we compare this finding with those of Sweeney (Table 4.2), we see an apparent mismatch. However, since explicit instruction is highly recommended generally (and Akerson and Abd-El-Khalick report a test of implicit instruction) the finding that teachers in all the lower grade levels believe that creativity is instructionally appropriate, this finding does not negate the recommendation explicitely to introduce the "creative aspects of NOS" in the early grades.

In a series of articles about young children's gains in NOS in a variety of contexts, Akerson and colleagues report that children in kindergarten through third grade made gains in all target areas of NOS when taught with an explicit-reflective approach: empiricism, the role of and distinction between observation and inference, creativity, tentativeness, subjectivity, and sociocultural embeddedness of NOS (Akerson and Donnelly 2010; Akerson et al. 2011a; Quigley et al. 2010). Overall, children appeared to make the greatest gains with respect to the role of empiricism, observation/inference, and the idea that science is tentative. Post-instruction, a greater number of children were able to articulate the role of creativity in science, and with greater sophistication, these trends were more pronounced with the older children.

Children were less successful gaining informed views of the cultural and subjective aspects of NOS with cultural embeddedness the most challenging aspect for teachers to model (Quigley et al. 2010). Collectively, these studies indicate that young children may be developmentally ready to learn these aspects of NOS, when taught with an explicit-reflective approach. Therefore, from the Akerson studies and that of Sweeney, we have important data regarding when certain NOS elements might be introduced. What logically comes next is consideration of how NOS ideas are scaffolded for learners throughout the grade levels with recognition of students' increasingly higher levels of conceptual development as they mature.

4.4.2 Considering Formal NOS Learning Progressions

There are several sources of proposed NOS learning progressions worthy of mention. Abd-El-Khalick (2012) has provided a generalized NOS progression that begins with basic instruction targeting the concept for lower elementary students continuing with greater levels of complexity into the higher grades. As an example, he discusses “tentativeness” and suggests that younger students can understand that knowledge in science can change, while older students should explore both how and why scientific conclusions might be replaced. In this specific example, student understanding would be scaffolded from a basic discussion that new information can expand or replace previous scientific understanding to more sophisticated notions such as change due to the reinterpretation of evidence because of new theoretical advances. The basic idea that science has a tentative character is therefore reexamined at increasingly higher levels of complexity that can also involve exploring links to other NOS aspects and science content. Erduran and Dagher (2014) too have considered the issue of learning progressions in their family resemblance approach (FRA) to NOS where students will encounter all or most targeted NOS elements each year. They have proposed alignments that are both connected to science content and to the age/grade of the students again with the recommendation of increasing sophistication.

One of the most complete, but regrettably often neglected, proposals for NOS learning progressions is found in the two volumes of the Project 2061 *Atlas for Scientific Literacy* (AAAS 2001, 2006). These two remarkable documents provide a series of “maps” outlining recommendations for when and at what level science content from *Benchmarks for Science Literacy* (1993), including NOS, should most effectively be taught. These recommendations arise from consideration of students’ prior conceptions and links to other science content coupled with a spiral curriculum philosophy whereby content is revisited at deeper levels of complexity for older students.

Atlas Volume I (AAAS 2001) includes much NOS-related material in the following sections related to “Scientific Inquiry” and includes “Evidence and Reasoning in Inquiry” (the role of data in science), “Scientific Investigations” (observations, repeatability, collection and recording relevant data, applying shared methods), “Scientific Theories” (ideas in science depend on data and may change with new data), and “Avoiding Bias in Science” (prior expectation, culture of science). NOS content in Atlas Volume II (AAAS 2006) is grouped into maps related to the Nature of Science including “Scientific World View” (science cannot address all questions, the universe operates in the same way), “The Scientific Community” (the processes of science can be used by all, there are shared methods and traditions in science), and “Science and Society” (society and scientists direct the work of science, science can add to public debates) and another map focused on “Technology and Science” (the relationship between science and technology/engineering).

It is impossible to thoroughly review the rich suggestions contained in these maps, but Fig. 4.2 shows a sample of part of the map addressing the topic of “Scientific Inquiry: Avoiding Bias in Science.” These Atlases synthesize in illustrative form much research in science education and as such could serve as templates to guide the development of textbooks and design of classroom instruction. Readers are encouraged to examine these maps in the original to consider the multitude of recommendations they offer about teaching key elements of NOS. Of course, documents such as they should be updated periodically to reflect current research findings. In the case of NOS, we know much more about young learners than we did

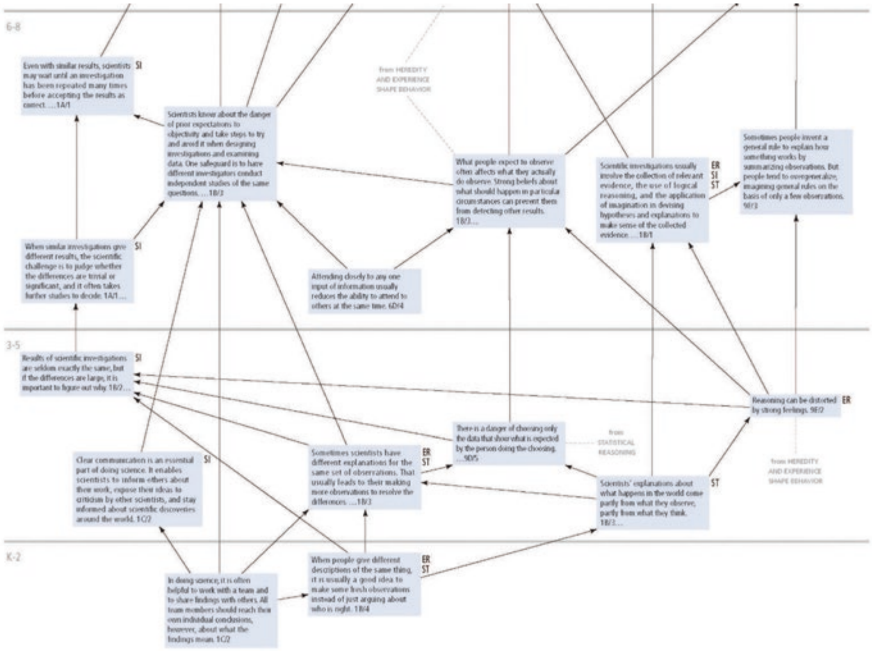


Fig. 4.2 This is a section of the recommended plan for teaching aspects of NOS from the Atlas of Scientific Literacy section targeting "Scientific Inquiry: Avoiding Bias in Science" (AAAS 2001, p. 23) which illustrated many attributes of learning progressions. Here, we see notes about the level of NOS content that would be appropriate for learners of various ages (Grades K-8) and links between aspects of NOS content and links to maps of other science content. The sample map illustrates how the same content can be included in the science curriculum at increasingly more complex levels for more sophisticated learners, a strategy that continues in the full version of this map for 9–12 grade students. (Permission to reproduce provided by the American Association for the Advancement of Science)

when the Atlases were originally produced, so these new insights could inform future proposals for NOS instruction. The US National Science Teachers Association is developing a new set of maps linked to the Next Generation Science Standards, a series of which will feature the NOS aspects included in that document.

4.4.3 Conclusions Regarding NOS Learning Progressions

As we look for definitive answers about the questions of "when" to teach NOS and "how much" NOS to teach, we should remember the caution of Bell (2006) who suggests that our concerns about NOS instruction must be tempered with evidence. Assumptions that are too strict about what learners can understand may limit what otherwise might be robust introductions to NOS for younger learners. Akerson et al. (2011a, b, 2014) believe as soon as children start to learn science in the kindergarten, learning about NOS should be included. Although their research demonstrates that students can gain understanding of many NOS aspects if explicitly taught, students should be exposed to different levels of knowledge depending on the character of specific NOS elements. These aspects of NOS learner readiness and proposals for NOS curricular scope and sequence should be the focus of increased research—particularly for secondary age students—by those with interests in the effective and appropriate inclusion of NOS in science teaching and learning.

4.5 NOS and Science Teacher Education

If we expect those who teach science to accurately infuse NOS into the science curriculum, they must possess accurate NOS content knowledge, value its importance, understand effective NOS pedagogy, and be motivated and skilled enough to put what they know into practice. However, having rarely experienced accurate NOS content instruction, preservice and in-service teachers possess many NOS misconceptions and often do not feel compelled to devote significant attention to it. Thus, NOS is a unique challenge for science teacher educators because they must provide instruction regarding both NOS content and pedagogy while also inspiring teachers to devote attention to NOS teaching and learning. Without a direct focus on NOS in science teacher education efforts, teachers are hardly in a position to accurately and effectively teach NOS.

Unfortunately, despite calls for improving teachers' NOS understanding through the inclusion of history and philosophy of science courses and related experiences in teacher preparation programs (see Abimbola 1983; Anderson et al. 1986; Gill 1977; Harms and Yager 1981; Kimball 1967; King 1991; Loving 1991; Manuel 1981; Martin 1972; Matthews 1989, 1994, 2015; Nunan 1977; Robinson 1969; and many others), Summers (1982) and Gallagher (1991) noted that undergraduate science and science teacher education programs do not seem to value and/or emphasize the philosophical background of science. Loving (1991) reported that of the 17 science teacher preparation programs she surveyed, 13% of undergraduate and 19% of graduate (post-graduate) students in those programs were required to take a philosophy of science course. Moreover, a traditional HPS course is unlikely sufficient preparation for accurately and effectively teaching NOS. The most recent study reporting NOS efforts in science teacher education (Backhus and Thompson 2006) noted that the majority of institutions (more than two-thirds) do not have a nature of science course of any variety and "at most perhaps 6% of preservice 9–12 science teachers will have taken such a course as a requirement" (p. 74). Lederman (2006) wrote what is still true, "there is not, and there has not been, a concerted professional development effort to clearly communicate, first, what is meant by 'NOS' and scientific inquiry and second, how a functional understanding of these valued aspects of science can be communicated to K–12 students" (p. 302). This point was echoed by Hodson (1988, p. 21) many years ago when he said:

> the frequent calls for philosophy of science to become a major component in teacher-training courses… have gone largely unheeded, so that there are now several generations of serving teachers with little or no understanding of basic issues in the philosophy of science and their significance in the design of effective learning experiences.

We are still determining the most effective ways to help teachers gain the necessary background that would encourage and assist them to put NOS knowledge into classroom practice. Therefore, wherever opportunities exist, we must help science teachers:

> develop deep, robust, and integrated NOS understandings [that] would have the dual benefits of not only enabling teachers to convey to students images of science and scientific practice that are commensurate with historical, philosophical, sociological, and psychological scholarship (teaching about NOS), but also to structure robust inquiry learning environments that approximate authentic scientific practice, and implement effective pedagogical approaches that share a lot of the characteristics of best science teaching practices (teaching with NOS) (Abd-El-Khalick 2013, p. 2087).

The following are four general options for teacher development often discussed within the science education community. Each has its own strengths and limitations.

4.5.1 NOS in Methods Courses or as Part of Science Pedagogy Professional Development

In this approach, NOS content and pedagogy are communicated as part of instruction regarding general research-based science-teaching practices. In preservice science teacher education programs, this would occur in a science methods course or series of science methods courses, whereas in in-service professional development, it might occur as part of efforts to promote science teachers' understanding of recent standards documents, the teaching of science through inquiry, or science content updates.

Advantages The central advantage to this approach is that NOS content is discussed in an environment where the curriculum and pedagogical connections can be immediately discussed. In this fashion, both NOS content, a rationale for its inclusion in science teaching, and the strategies for teaching that content will be conveyed to prospective science teachers. In addition, because methods courses are often tied to practicum experience, both preservice and in-service teachers have the needed opportunities to implement what they are learning with students in schools. Finally, this approach is conducive to addressing the parallels between the difficulties that scientists have in making sense of the natural world and the difficulties students have in learning science ideas.

Disadvantages The main disadvantage associated with blending NOS with methods courses or science pedagogy professional development is one of too little time and lack of a science context. Both NOS content and NOS pedagogy are complex and nuanced. Addressing NOS along with the other crucial aspects of the methods course or professional development experience will almost assuredly shortchange NOS, general research-based science-teaching practices, or both. General science-teaching practices and NOS instructional practices are both complex, and enough time must be devoted to each while exploring their synergistic relationship. Moreover, akin to decontextualized NOS learning experiences, when a more authentic science context is lacking, NOS ideas learned in methods courses or pedagogical professional development experiences may not be robustly accepted as accurately reflecting science and scientists.

4.5.2 NOS in Science Content Experiences

In this approach, preservice and in-service teachers in science courses or science content-enriching experiences will have appropriate NOS issues raised that are relevant to the science content being addressed. This approach reflects what has previously been put forth for teaching K-12 science but is also recommended for science instruction for any purpose or level.

Advantages The most significant advantage to this approach is that NOS ideas are likely to be viewed as more credible when linked to science content. Also, teachers who experience NOS learning linked to science content instruction will be able to visualize how these two may be seamlessly linked. This would help legitimize NOS in science teaching and learning in a way that merely encountering it in a decontextualized fashion may not. For example, Donnelly and Argyle (2011) reported that teachers, after completing physical science professional development in which NOS and NOS activities were overtly discussed, used many of these activities later in their own classrooms.

Disadvantages Central among the disadvantages of this approach is that few post-secondary science instructors are likely to devote significant attention to NOS or know how to teach it effectively. Also, because the focus of science courses and science content professional development is on the traditional science content, providing enough attention to NOS issues and NOS pedagogy resources is unlikely. The critical challenge to this approach is how science teachers will learn specific strategies that will permit them to integrate NOS in their classes.

4.5.3 NOS in the Context of Scientific Research Experiences

This approach has teachers take part in authentic research experiences so that they have some experience with how science is done. These sorts of experiences often occur in a summer or semester-long program in which teachers work directly with scientists in authentic research experiences (see Chap. 30 for an extended discussion of this opportunity).

Advantages Working with scientists who are doing science bolsters confidence that whatever might be learned about NOS will be convincing to teachers, and such firsthand experiences can inspire them to teach NOS with authority and enthusiasm and in a fully contextualized fashion. Another advantage is that those who have had such experiences will be more able to guide students in pursuing their own research and science fair projects. Morrison et al. (2009) report that working with scientists benefited elementary teachers: "Teachers did improve their views of the NOS and were able to apply the characteristics of science that they learned about during instruction to what they saw happening at the research facility" (p. 398). In addition, teachers who may have held stereotypical views about scientists and their work began to change their ideas through daily, informal interactions with scientists.

Disadvantages Many studies of teachers taking part in authentic research experiences report little growth in NOS understanding and instruction. This is not particularly surprising, for reasons noted earlier in this chapter: engaging in science practices is not equivalent to understanding NOS, and scientists themselves possess NOS misunderstandings. As early as 1961, Behnke investigated a group of scientists and a group of secondary science teachers regarding NOS and science and society and found that more than half of the teachers and 20% of the scientists incorrectly viewed the content of science as fixed and unchangeable. Two primary challenges with the teacher-research-experience approach are (1) that few scientist-mentors reflect on, and thus are aware of, important NOS issues related to their work and science education efforts, and hence, they do not draw teachers' attention to NOS, and (2) that such research experiences will not prepare teachers to teach NOS if they are unaware of research regarding effective NOS instruction.

4.5.4 NOS-Focused Science Education Courses and/or Professional Development

This approach has science teachers learn about NOS in a discrete course or professional development experience taught by a science educator well versed in the social studies of science. While formal courses in the history and philosophy of science taught by experts in those fields are interesting and informative, they do not draw teachers' attention to NOS issues important for science education efforts. Abd-El-Khalick and Lederman (2000b) followed teachers in a HOS-focused class and reported that NOS understanding improved little unless they had previously experienced explicit NOS instruction. Even then, formal courses in the history and philosophy of science do not prepare teachers to teach NOS effectively.

Advantages A dedicated "NOS in science education" experience taught by a science educator well versed in the social studies of science is more likely to provide sufficient attention to (1) rationales for accurate NOS teaching and learning, (2) NOS ideas and issues most relevant to science education purposes and personal/societal decision-making, and (3) research regarding effective NOS instruction. Important nuances in NOS understanding and pedagogy can also be addressed, as well as many other important pedagogical issues appearing in this book, that require more time than is permitted by a science methods course or by typical professional development experiences. Finally, a dedicated NOS course or professional development experience is also more likely to occur over several months, permitting teachers to wrestle with and develop a more robust understanding of accurate and effective NOS teaching and learning.

Disadvantages A discrete NOS course or professional development experience requires instructional expertise, effort and time, which, for a variety of reasons, may deter science education faculty and teachers. Backhus and Thompson (2006) reported that few US preservice programs in science education require prospective teachers complete a course solely focused on NOS and the related pedagogical strategies. Not surprisingly, research evidence reveals that the more time devoted to NOS the better. As Akerson et al. (2006) point out, NOS as part of a single methods course is unlikely to be enough to produce the necessary understanding of and commitment to accurate and effective instruction in this area. Bell et al. (2016) noted some success with a two-method course model in which NOS was addressed, while Herman et al. (2013b) and Kruse et al. (2017) studied students at various points in a four-class (three semesters) teacher preparation program and found one course did not generate both NOS understanding and NOS instructional rationales and pedagogical skills necessary for successful implementation, but both matured during the sequence of classes. Few science teacher preparation programs will have such a focus on NOS, but perhaps some combination of initial exposure to NOS and follow-up with in-service teacher development is a reasonable recommendation to enhance practice.

4.5.5 Summary and Synergistic Approaches to NOS Teacher Preparation

Each of the four approaches for preparing teachers to teach NOS accurately and effectively has both merit and drawbacks. Of course, these approaches are not mutually exclusive, and some combination of them might be effective while mitigating their respective disadvantages. Importantly, although numerous studies employing the above approaches and key characteristics of effective NOS instruction have shown that teachers' NOS content understanding can be improved (Akindehin 1988; Barufaldi et al. 1977; Cossman 1969; Herman and Clough 2016; Wahbeh and Abd-El-Khalick 2014), efforts to promote accurate and effective NOS classroom instruction have been largely disappointing. A notable exception is a study by Herman et al. (2013b) that investigated 13 teachers 2–5 years after they completed a teacher education program with multiple science methods courses and a class on NOS in science education. They found that 12 of the teachers explicitly taught NOS, and 9 did so at moderate to high levels. So, while future research must focus on determining how best to promote teachers' implementation of accurate and effective NOS instruction, reason exists to remain optimistic that this important goal can be achieved.

4.6 Assessing NOS Teaching and Learning

4.6.1 Assessing NOS Instruction

A concern with NOS research efforts is the lack a transparent and common method for assessing science teachers' NOS instructional practices. The lack of transparency is problematic for understanding the fidelity of NOS instructional efforts, and the lack of a common method for assessing NOS instructional practices makes it difficult to compare studies that investigate teachers' practices and their impact on students' NOS understanding.

To promote a more transparent and consistent account of research regarding teachers' NOS implementation practices, Herman et al. (2013b) created an evaluation instrument called the Nature of Science Classroom Observation Protocol (NOS-COP). The NOS-COP is a tool for assessing and reporting NOS implementation based on guidelines (e.g., NOS accuracy, explicit referral to NOS, and level of NOS contextualization) informed by established NOS science education literature (Abd-El-Khalick and Lederman 2000a; Clough 2006; Khishfe and Abd-El-Khalick 2002; Khishfe and Lederman 2006). Herman et al. (2013b) write:

> The instrument provides a means for standardizing classroom observations regarding NOS classroom implementation practices and adds needed nuances and clarity to such research. For instance, in reviewing many prior studies addressing teachers' NOS implementation practices, much of what those teachers did and did not do is unclear. For this reason, com-

> paring the outcomes of studies investigating teachers' NOS implementation practices is at best haphazard without a clear and transparent NOS classroom research protocol and scoring guide. The NOS-COP instrument…is designed to advance that clarity and transparency in NOS implementation research. (pp. 297–298)

The NOS-COP follows the same format as the Local Systemic Change Classroom Observation Protocol (LSC-COP; Horizon Research Inc. 2006). This congruence between the NOS-COP and LSC-COP enables researchers to consider teachers' NOS implementation and science-teaching practices more broadly (Herman et al. 2013a). Just as use of the LSC-COP is to be preceded by a teacher interview so that the context of the observed lessons and artifacts can be better understood, when using the NOS-COP instrument, unstructured interviews should be conducted with study participants before and after observing lessons, to acquire a more comprehensive and accurate view of observed lessons.

4.6.2 Assessing NOS Learning

Accurately assessing NOS understanding is important for several reasons. Obviously, determining to what extent students comprehend targeted NOS ideas after instruction is important. Accurately assessing students' NOS thinking prior to instruction is also important for guiding teachers' decision-making. Including NOS assessment on high-stakes exams also sends a clear message to teachers and students about the importance of teaching and learning NOS. In that sense, assessment is a "policy lever" because coupling the desired goal of NOS understanding with its inclusion on high-stakes exams will increase attention to NOS by textbook authors, media developers, curriculum innovators, teachers, school administrators, and the public.

However, no valid and reliable way presently exists to assess NOS understanding in a manner that is suitable for high-stakes exams and for teachers who work with large groups of students. Wahbeh and Abd-El-Khalick (2014) have acknowledged that the lack of easily accessible NOS assessment tools may work against the inclusion of NOS in curricula. Furthermore, lacking such NOS assessments, researchers are hampered in their efforts to accurately determine NOS understanding among members of the public and in studies with large numbers of participants. Thus, we reiterate and emphasize what many have said about NOS assessment that an urgent need exists for measures that target all NOS sub-elements, are efficient in their administration, and are applied both in classroom and high-stakes settings.

Various NOS assessment instruments have been developed in the past half-century, but each is problematic for a variety of reasons that we discuss below. However, with this warning in mind, some of the more widely used measures have included *Nature of Science Scale* (NOSS; Kimball 1967), *Nature of Scientific Knowledge Scales* (NSKS; Rubba 1976), *Conception of Scientific Theories Test* (COST; Cotham and Smith 1981), and *Views on Science-Technology-Society*

(VOSTS; Aikenhead et al. 1989). Currently, *Views of the Nature of Science*[1] (VNOS; Lederman et al. 2002), *Student Understanding of Science and Scientific Inquiry* (SUSSI; Liang et al. 2008), and *Students' Ideas about Nature of Science* (SINOS; Chen et al. 2013) are often featured in research studies. For a more complete consideration of the state of NOS instruction, readers will find the overview provided by Lederman et al. (2014) useful.

Several major challenges have hindered the development of NOS assessment tools. First, Aikenhead (1988) demonstrated that the accuracy of information concerning student beliefs about STS topics (with implications for NOS) is highest when assessed with semi-structured interviews and declines when examined through empirical multiple-choice instruments, essay instruments, or Likert-type tools. Likert and multiple-choice responses assume that both students and researchers perceive the meanings of concepts in the same way, an assumption that has been criticized (Aikenhead and Ryan 1992; Lederman and O'Malley 1990; Munby 1982).

As an example, consider this statement from Aikenhead and Ryan (1992):

> "Scientific knowledge is tentative" was a statement on the *Science Process Inventory* (SPI) (Welch 1966) with which high school students were asked to agree or disagree. Aikenhead (1979) discovered that when offered the chance to respond, "I do not understand," more than a quarter of grade 11 and 12 students did so. Therefore, whenever students responded "agree" or "disagree" to the SPI item "scientific knowledge is tentative," a number of those students simply did not understand what the statement meant. (p. 478)

Aikenhead et al. (1987) add:

> When students process and respond to an objectively scored item, they subjectively make their own meaning out of the item. The standardized tests may be objective to the scorer, but they turn out to be quite subjective to the student. By shifting the responsibility for handling subjectivity to the mature adult researcher, one can discern diversity and insight "objectively" described by students. (p. 148)

Second, NOS issues are nuanced and often depend on context. For instance, some scientific knowledge is tentative, while other ideas in science, such as the existence of atoms, are so well established that they are accepted, with good reasons, as the way nature really is. Expressions of many NOS ideas, like that of the certainty of scientific knowledge, will be influenced by circumstances, and this makes generic NOS assessments problematic.

A third assessment concern is related to what ends are sought when NOS knowledge is measured. NOS instruments have been designed primarily to determine understanding of general NOS ideas in relation to science. However, others seek to determine NOS understanding in the context of SSIs, arguing that there is little use for NOS understanding if it does not inform everyday decision-making (e.g., Allchin 2011).

A fourth issue relates to the level of agreement among educators regarding the aspects of NOS that we want students to understand. While no one would suggest

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[1] The most frequently used NOS assessment tool is the VNOS instrument which has been revised many times but still faces criticisms (e.g., Allchin 2011).

that we ought to have students memorize some decontextualized list of NOS learning goals, NOS teaching and learning efforts will suffer from this misapplication if educators are not careful. Perhaps any set of NOS learning objectives will face some criticism, but that must not stop progress in developing valid and reliable NOS assessments. For instance, some may advocate for including the realist/instrumentalist distinction as part of NOS instruction in science class, yet that is not one of the key NOS elements commonly recommended. However, it could be included in instruction and assessed if desired. Another example is the call for classroom discussions regarding the relationship between funding and work in science (e.g., Erduran and Dagher 2014; Clough, Chapter 15). This NOS issue can be argued to fit under the key NOS domain "human elements of science" (see Fig. 3.1 in Chap. 3), and perhaps this aspect of NOS should be more explicitly mentioned as part of the "human elements" domain. Regardless, NOS assessment efforts can and should proceed, focusing on agreed-upon NOS learning outcomes, while those advocating other outcomes can put forward additional assessment items.

A fifth issue related to NOS assessment is the time required for its implementation. Assessment approaches that require a significant amount of time to administer, along with time and expertise (training) to score, are unreasonable for classroom teachers or for use in high-stakes exams. The NOS assessment issues we have raised here are not a criticism of past efforts but rather are certainly an admission of the difficulties faced by the NOS research and practice communities. While these assessment issues are formidable, none is insurmountable. No single NOS assessment instrument will address all concerns and meet all goals. However, one way out of this apparent morass will almost assuredly rest in designing a bank of instruments and items to meet specific goals. We recommend that work should begin immediately on this crucial and long-neglected task. Accomplishing this will assist immensely in efforts to have NOS take its rightful place as an important aspect of school science instruction. Teachers, researchers, and those seeking school accountability all must have access to valid and reliable NOS assessments that are appropriate for their purposes. As many have noted, in education settings we most often assess what we value—and, conversely, what we assess tells others (including students) what is valuable. Therefore, robust NOS assessment should be as much a part of school science as measurement of traditional science content.

4.7 Teaching About NOS: Challenges and Considerations

Much has been written regarding obstacles to teaching NOS accurately and effectively as part of science instruction (e.g., Clough and Olson 2012; Herman et al. 2017; and in Chap. 13 in this book). In this section, we will focus on some of the most significant challenges we currently face with the implication that these areas would benefit from additional focus by researchers.

4.7.1 Teachers Have Limited Understanding of NOS Knowledge, Content, and Pedagogy

Scores of studies support the claim that most teachers possess NOS misconceptions that could easily interfere with their ability to communicate this content accurately. Schwartz and Lederman (2002) note that having an informed and accurate knowledge of both NOS and science content is a primary factor for teaching NOS effectively. Deep understanding of NOS and the associated science subject matter, along with an understanding of the relationships between the two, plays a crucial role in teachers' NOS classroom practice.

Understandings such as these are essential for developing NOS pedagogical content knowledge (NOS PCK), a concept first discussed by Abd-El-Khalick (1997) and defined recently as "teachers' understandings of NOS and the relationship between such understanding and teaching it" (Akerson et al. 2017, p. 298). In a sense, this entire book is dedicated to helping teachers develop NOS PCK by understanding the history of, and rationales for, the inclusion of NOS in classroom science.

Not surprisingly, many consider NOS PCK the most essential factor related to successful NOS classroom practice. Abd-El-Khalick et al. (1998) suggest that teachers should possess knowledge of NOS such that it could be applied with different content and with diverse groups of learners. Schwartz and Lederman (2002) tell us that teachers must be able to develop and/or review lesson plans and activities related to NOS, and Hanuscin (2013) adds that teachers must have knowledge of NOS assessment to have useful NOS PCK. These views are substantiated by Wahbeh and Abd-El-Khalick (2014), who investigated teachers' classroom practices and found that successful inclusion of NOS is based on teaching with:

> (a) broad heuristic understandings of the target NOS dimension embedded in some HPSS [history, philosophy, and sociology-of-science] context, (b) deep understandings of the target science content, (c) situated perceptions of that NOS dimension in relation to the target science content, which derives from knowledge of associated HPSS narrative(s) for central science concepts in the domain, and (d) understandings and skills needed to enact student-centered inquiry learning environments, including attention to students' prior knowledge and the ability to engage students with inquiries that help them build understandings of the target science domain. (p. 462)

4.7.2 Teachers Place Limited Value on NOS Teaching and Learning

Teachers' beliefs about education, teaching, and learning represent another suite of crucial factors related to their ultimate classroom practice (Waters-Adams 2006). Brickhouse (1990) investigated relations between science teachers' conceptions of

NOS and their knowledge and beliefs about the teaching and learning of science. The results showed that for experienced teachers, knowledge and beliefs about science, subject matter, teaching and learning, and students are highly related. Schwartz and Lederman (2002) also evaluated this issue with respect to NOS and found that classroom practice success is connected to teachers' knowledge of NOS and their intentions to teach it. Studies such as these and others demonstrate that teachers must know about and value NOS if they are to teach it and do so effectively. Unfortunately, most teachers do not understand or exhibit value for NOS (Lee and Witz 2009). This, coupled with other factors such as poor representation of NOS in standards documents and in teaching materials, often negatively affects teachers' overall beliefs with respect to NOS instruction, accounting for its lack of appearance in the science classroom.

Related to the issue of beliefs are documented concerns that teachers have regarding the inclusion of NOS as an instructional goal that may lead them to omit NOS from classroom instruction. Some teachers maintain that NOS is too abstract and difficult for students to learn (Abd-El-Khalick and Lederman 2000a). Many teachers cite pressure to cover traditional science content (Abd-El-Khalick and Lederman 2000a) and are worried about the consequences of teaching NOS when traditional science content takes priority (Akerson and Donnelly 2008; Wahbeh and Abd-El-Khalick 2014). These fears parallel those expressed by even novice teachers who note typical "survival" issues (Wahbeh and Abd-El-Khalick 2014) such as time concerns (Lederman 1999) and classroom management issues (Akerson and Donnelly 2008). Peer pressure also deters attention to NOS instruction, because teachers often feel compelled to keep their instruction aligned with other teachers' who ignore accurate NOS instruction (Akerson and Donnelly 2008; Herman et al. 2017). Finally, preservice teachers rarely have mentors who value and support NOS instruction (Akerson et al. 2010; Herman et al. 2017). Despite extensive scholarship and science standards documents noting the importance of NOS understanding, teaching, and learning, NOS often remains at odds with expectations for science teaching in schools (Lakin and Wellington 1994).

4.7.3 A Lack of NOS-Focused Instructional Materials

Effectively translating any content into robust plans for teaching and learning is complex and difficult. Exacerbating this struggle is the rare attention paid to NOS in textbooks and supporting classroom curriculum materials that might otherwise encourage teachers to address NOS and assist in developing their NOS PCK (Abd-El-Khalick and Lederman 2000a; Akerson et al. 2010; Wahbeh and Abd-El-Khalick 2014). Science teachers are also largely unaware of the growing online resources dedicated to accurate and effective NOS instruction. Teachers' dependence on science textbooks and supporting materials that lack a focus on NOS is well documented (Banilower et al. 2013; Stake and Easley 1978; Weiss 1993; Weiss et al. 2003). Thus, having no clear guidance on how to include NOS instruction in everyday lessons, teachers do not implement such instruction, and NOS is likely not even part of their instructional thinking. Nearly two decades ago, Lederman (1999) noted this:

> The development of a wide variety of instructional routines and schemes that allow beginning teachers to feel comfortable with the organization and management of instruction appears to be a critical prerequisite for any efforts to assist beginning teachers' attempts to promote students' understandings of the nature of science. (p. 927)

Akerson et al. (2010) call for adapting and modifying curricula to emphasize NOS while supporting traditional science content instruction. Hanuscin et al. (2011) go further in reminding all concerned that professional developers and textbook authors must develop curriculum materials to support NOS instruction. One model for this curriculum development is offered by Lin et al. (2012), who have produced a teachers' guide related to NOS. In it they discuss NOS concepts, sample NOS curriculum guidelines, talk about how to engage students with targeted questions, and provide some models for NOS assessment. While we are not endorsing any single plan for NOS instruction, Lin et al. have given much thought to the challenges of NOS instruction and their potential solutions.

4.7.4 NOS Is Not Viewed as Important as "Traditional" Science Content: The Challenge of Reform Documents

We end this section discussing challenges of NOS instruction by discussing the pernicious issue that continues to work against the inclusion of NOS elements in the science curriculum. Even though members of the science education community embraces NOS teaching and learning, NOS goals are rarely given clarity or prominance. If science standards and other reform documents fail to include or emphasize NOS, schools, teachers, textbook writers, and assessment design professional will likely also ignore this vital content.

McComas and Olson (1998) reported more than two decades ago that many countries then were beginning to include NOS-related content in their national standards. They expected and hoped that this trend would continue, and in some educational settings, this has been the case, but progress is not universal. In a recent study by Olson (2018) of standards documents from nine countries, she found that in most of the documents, attention to NOS appears only in front/back matter or headers, but not as overt learning outcomes for students. Only in four of the nine countries' documents studied did NOS appear in student expectations; only one included NOS consistently throughout the document. Documents that did address the NOS tended to express support only in the introductions and then neglected it when putting forth more specific objectives for traditional science content and process skills.

So, despite years of research and conversation about the importance of NOS, in most instances the NOS seems to barely appear even as a consideration among stakeholders.

In the United States, the Next Generation Science Standards (Achieve 2013) were released with the hope that many states would adopt its recommendations. At the time of this writing, 19 states and the District of Columbia (about 35% of all US students) are guided by NGSS. As McComas and Nouri (2016) discuss in detail, NOS is included in NGSS and represented by many widely recommended elements. However, the discussion of NOS is relegated to an appendix. Furthermore, the NOS objectives appearing in the main text of NGSS are inexplicably linked to other more visible learning goals such as crosscutting themes and science and engineering practices. Those who wrote and approved the NGSS have regrettably marginalized NOS and/or did not appreciate the importance of including this content as overt and prominent student outcomes. We might be pleased that a reasonably robust set of NOS learning objectives is found in this important document, but given the implicit way that NOS is represented, teachers are unlikely to value NOS, nor will textbook authors, curriculum designers, and assessment developers see that NOS has equal status with what we have been calling "traditional science content."

4.8 Conclusions

This chapter reports that much has been learned about accurate and effective NOS teaching and learning. We have seen an increase in the inclusion of NOS-related objectives in science-teaching documents, and generally teachers are becoming increasingly aware of this domain. However, little of what is known is widely implemented in school science, and science educators must focus more deliberately on including NOS in science standards and assessment at all levels, on preparing teachers to engage students in meaningful NOS lessons, and on the development of engaging, NOS-centered curricula. Student understanding of fundamental science ideas is important, but equally important is understanding the nature of science (how scientists do their work, what doing science is like, how science ideas are developed and substantiated, and how science and society impact one another). Basic science content and NOS understanding must both be at the foundation for all high-quality science teaching and learning plans. NOS understanding plays an important role in teaching and student understanding of science content, it assists in developing a richer appreciation of the scientific enterprise, in defending conclusions based on science, criticizing those who falsely claim a scientific basis for ill-formed conclusions, making informed personal and societal decisions involving science, and generally valuing science as a way of knowing that impacts humankind.

References

Abd-El-Khalick, F. (1997). *Improving prospective and practicing science teachers' conceptions of the nature of science.* Unpublished scholarly library research paper presented to the faculty and doctoral students. Department of Science and Mathematics Education, Oregon State University, Corvallis, OR.

Abd-El-Khalick, F. (2005). Developing deeper understandings of nature of science: The impact of a philosophy of science course on preservice science teachers' views and instructional planning. *International Journal of Science Education, 27*(1), 15–42.

Abd-El-Khalick, F. (2012). Nature of science in science education: Toward a coherent framework for synergistic research and development. In B. J. Fraser, K. Tobin, & C. McRobbie (Eds.), *Second international handbook of science education* (Vol. 2, pp. 1041–1060). Dordrecht: Springer.

Abd-El-Khalick, F. (2013). Teaching with and about nature of science, and science teacher knowledge domains. *Science & Education, 22*(9), 2087–2107.

Abd-El-Khalick, F., & Akerson, V. L. (2004). Learning as conceptual change: Factors mediating the development of preservice elementary teachers' views of nature of science. *Science Education, 88*(5), 785–810.

Abd-El-Khalick, F., & Akerson, V. (2009). The influence of metacognitive training on preservice elementary teachers' conceptions of nature of science. *International Journal of Science Education, 31*(16), 2161–2184.

Abd-El-Khalick, F., & Lederman, N. G. (2000a). Improving science teachers' conceptions of nature of science: A critical review of the literature. *International Journal of Science Education, 22*(7), 665–701.

Abd-El-Khalick, F., & Lederman, N. G. (2000b). The influence of history of science courses on students' views of nature of science. *Journal of Research in Science Teaching, 37*(10), 1057–1095.

Abd-El-Khalick, F., Bell, R. L., & Lederman, N. G. (1998). The nature of science and instructional practice: Making the unnatural natural. *Science Education, 82*(4), 417–436.

Abd-El-Khalick, F., Waters, M., & Le, A. P. (2008). Representations of nature of science in high school chemistry textbooks over the past four decades. *Journal of Research in Science Teaching, 45*(7), 835–855.

Abimbola, O. A. (1983). The relevance of the "new" philosophy of science for the science curriculum. *School Science and Mathematics, 83*, 183–190.

Achieve. (2013). The next generation science standards. Retrived August 8, 2019. https://www.nextgenerationscience.org.

Adúriz-Bravo, A., & Izquierdo-Aymerich, M. (2009). A research-informed instructional unit to teach the nature of science to pre-service science teachers. *Science & Education, 18*(9), 1177–1192.

Aikenhead, G. S. (1979). Using qualitative data in formative evaluation. *Alberta Journal of Educational Research, 25*(2), 117–129.

Aikenhead, G. S. (1988). An analysis of four ways of assessing student beliefs about STS topics. *Journal of Research in Science Teaching, 25*(8), 607–629.

Aikenhead, G. S., & Ryan, A. G. (1992). The development of a new instrument: "Views on Science-Technology-Society" (VOSTS). *Science Education, 76*(5), 477–491.

Aikenhead, G. S., Fleming, R. W., & Ryan, A. G. (1987). High school graduates' beliefs about science-technology-society. I. Methods and issues in monitoring student views. *Science Education, 71*(2), 145–161.

Aikenhead, G. S., Ryan, A. G., & Fleming, R. W. (1989). *Views on Science-Technology-Society*, Form CDN.mc.5. Department of Curriculum Studies, College of Education, University of Saskatchewan. Available at https://www.usask.ca/education/documents/profiles/aikenhead/index.htm

Akerson, V. L., & Abd-El-Khalick, F. (2003). Teaching elements of nature of science: A yearlong case study of a fourth-grade teacher. *Journal of Research in Science Teaching, 40*, 1025–1049.

Akerson, V. L., & Abd-El-Khalick, F. (2005). “How should I know what scientists do—I am just a kid”: Fourth grade students’ conceptions of nature of science. *Journal of Elementary Science Education, 17*, 1–11.

Akerson, V. L., & Donnelly, L. A. (2008). Relationships among learner characteristics and preservice elementary teachers’ views of nature of science. *Journal of Elementary Science Education, 20*(1), 45–58.

Akerson, V. L., & Donnelly, L. A. (2010). Teaching nature of science to K-2 students: What understandings can they attain? *International Journal of Science Education, 32*(1), 97–124.

Akerson, V. L., Abd-El-Khalick, F., & Lederman, N. G. (2000). Influence of a reflective explicit activity-based approach on elementary teachers’ conceptions of nature of science. *Journal of Research in Science Teaching, 37*(4), 295–317.

Akerson, V. L., Morrison, J. A., & Roth-McDuffie, A. (2006). One course is not enough: preservice elementary teachers’ retention of improved views of nature of science. *Journal of Research in Science Teaching, 43*(2), 194–213.

Akerson, V. L., Hanson, D. L., & Cullen, T. A. (2007). The influence of guided inquiry and explicit instruction on K-6 teachers’ views of nature of science. *Journal of Science Teacher Education, 18*(5), 751–772. https://doi.org/10.1007/s10972-007-9065-4.

Akerson, V. L., Buzzelli, C. A., & Donnelly, L. A. (2010). On the nature of teaching nature of science: Preservice early childhood teachers’ instruction in preschool and elementary settings. *Journal of Research in Science Teaching, 47*(2), 213–233.

Akerson, V. L., Buck, G. A., Donnelly, L. A., Nargund-Joshi, V., & Weiland, I. S. (2011a). The importance of teaching and learning nature of science in the early childhood years. *Journal of Science Education and Technology, 20*(5), 537–549.

Akerson, V. L., Weiland, I. S., Pongsanon, K., & Nargund, V. (2011b). Evidence-based strategies for teaching nature of science to young children. *Journal of Kırşehir Education, 11*(4), 61–78.

Akerson, V. L., Weiland, I. S., Nargund-Joshi, V., & Pongsanon, K. (2014). Becoming an elementary teacher of nature of science: Lessons learned for teaching elementary science. In *Science teacher educators as K-12 teachers* (pp. 71–87). Dordrecht: Springer.

Akerson, V. L., Pongsanon, K., Rogers, M. A. P., Carter, I., & Galindo, E. (2017). Exploring the use of lesson study to develop elementary preservice teachers’ pedagogical content knowledge for teaching nature of science. *International Journal of Science and Mathematics Education, 15*(2), 293–312.

Akindehin, F. (1988). Effect of an instructional package on preservice science teachers’ understanding of the nature of science and acquisition of science-related attitudes. *Science Education, 72*(1), 73–82.

Allchin, D. (2003). Scientific myth-conceptions. *Science Education, 87*(3), 329–351.

Allchin, D. (2004). Pseudohistory and pseudoscience. *Science & Education, 13*(3), 179–195.

Allchin, D. (2011). Evaluating knowledge of the nature of (whole) science. *Science Education, 95*(3), 518–542.

Allchin, D. (2013). Problem-and case-based learning in science: An introduction to distinctions, values, and outcomes. *CBE-Life Sciences Education, 12*(3), 364–372.

Allchin, D., Andersen, H. M., & Nielsen, K. (2014). Complementary approaches to teaching nature of science: Integrating student inquiry, historical cases, and contemporary cases in classroom practice. *Science Education, 98*(3), 461–486.

American Association for the Advancement of Science. (1993). *Benchmarks for science literacy*. New York: Oxford University Press.

American Association for the Advancement of Science. (2001). *Atlas of science literacy: Mapping K-12 learning and goals*. Washington: Author.

American Association for the Advancement of Science. (2006). *Atlas of science literacy: Mapping K-12 learning and goals. Volume II*. Washington, DC: Author.

Anderson, H. O., Harty, H., & Samuel, K. V. (1986). Nature of science, 1969 and 1984: Perspectives of preservice secondary science teachers. *School Science and Mathematics, 86*, 43–50.

Appleton, K. (1997). Analysis and description of students’ learning during science classes using a constructivist-based model. *Journal of Research in Science Teaching, 34*(3), 303–318.

Backhus, D. A., & Thompson, K. W. (2006). Addressing the nature of science in preservice science teacher preparation programs: Science educator perceptions. *Journal of Science Teacher Education, 17*(1), 65–81.

Banilower, E. R., Smith, P. S., Weiss, I. R., Malzahn, K. A., Campbell, K. M., & Weis, A. M. (2013). *Report of the 2012 National Survey of Science and Mathematics Education*. Chapel Hill: Horizon Research. Available at http://www.horizon-research.com/2012nssme/wp-content/uploads/2013/02/2012-NSSME-Full-Report1.pdf.

Barufaldi, J. P., Bethel, L. J., & Lamb, W. G. (1977). The effect of a science methods course on the philosophical view of science among elementary education majors. *Journal of Research in Science Teaching, 14*(4), 289–294.

Beane, J. A., & Apple, M. W. (1995). The case for democratic schools. In M. W. Apple & J. A. Beane (Eds.), *Democratic schools* (pp. 1–25). Alexandria: ASCD.

Behnke, F. L. (1961). Reactions of scientists and science teachers to statements bearing on certain aspects of science and science teaching. *School Science and Mathematics, 61*(3), 193–207.

Bell, R. L. (2006). Perusing Pandora's box: exploring the what, when, and how of nature of science instruction. In L. B. Flick & N. G. Lederman (Eds.), *Scientific inquiry and nature of science* (pp. 427–446). Dordrecht: Springer.

Bell, P., & Linn, M. C. (2000). Scientific arguments as learning artifacts: Designing for learning from the web with KIE. *International Journal of Science Education, 22*(8), 797–817.

Bell, R. L., Matkins, J. J., & Gansneder, B. M. (2011). Impacts of contextual and explicit instruction on preservice elementary teachers' understandings of the nature of science. *Journal of Research in Science Teaching, 48*, 414–436.

Bell, R. L., Mulvey, B. K., & Maeng, J. L. (2016). Outcomes of nature of science instruction along a context continuum: Preservice secondary science teachers' conceptions and instructional intentions. *International Journal of Science Education, 38*(3), 493–520.

Brickhouse, N. W. (1990). Teachers' beliefs about the nature of science and their relationship to classroom practice. *Journal of Teacher Education, 41*(3), 53–62.

Carey, S., & Smith, C. (1993). On understanding the nature of scientific knowledge. *Educational Psychologist, 28*(3), 235–251.

Chen, S., Chang, W. H., Lieu, S. C., Kao, H. L., Huang, M. T., & Lin, S. F. (2013). Development of an empirically based questionnaire to investigate young students' ideas about nature of science. *Journal of Research in Science Teaching, 50*(4), 408–430.

Clark, R. L., Clough, M. P., & Berg, C. A. (2000). Modifying cookbook labs: A different way of teaching a standard laboratory engages students and promotes understanding. *The Science Teacher, 67*(7), 40–43.

Clough, M. P. (2002). Using the laboratory to enhance student learning. In R. W. Bybee (Ed.), *Learning science and the science of learning* (pp. 85–94). Washington, DC: National Science Teachers Association.

Clough, M. P. (2006). Learners' responses to the demands of conceptual change: Considerations for effective nature of science instruction. *Science & Education, 15*(5), 463–494.

Clough, M. P. (2007). Teaching the nature of science to secondary and post-secondary students: Questions rather than tenets. *The Pantaneto Forum, 25*. http://pantaneto.co.uk/issue-25/

Clough, M. P. (2011a). Teaching and assessing the nature of science: How to effectively incorporate the nature of science in your classroom. *The Science Teacher, 78*(6), 56–60.

Clough, M. P. (2011b). The story behind the science: Bringing science and scientists to life in post-secondary science education. *Science & Education, 20*(7–8), 701–717.

Clough, M. P. (2015). Role of visual data in effectively teaching the nature of science. In K. D. Finson & J. Pedersen (Eds.), *Application of visual data in K–16 science classrooms*. Charlotte: Information Age.

Clough, M. P. (2017). History and nature of science in science education. In K. Taber & B. Akpan (Eds.), *Science education: An international course companion* (pp. 39–51). Rotterdam: Sense.

Clough, M. P., & Olson, J. K. (2012). Impact of a nature of science and science education course on teachers' nature of science classroom practices (Chapter 12). In M. S. Khine (Ed.), *Advances in nature of science research: Concepts and methodologies*. Dordrecht: Springer.

Clough, M. P., Berg, C. A., & Olson, J. K. (2009). Promoting effective science teacher education and science teaching: A framework for teacher decision-making. *International Journal of Science and Mathematics Education, 7*(4), 821–847.

Corcoran, T., Mosher, F.A., & Rogat, A. (2009). *Learning progressions in science: An evidence-based approach to reform* (Consortium for Policy Research in Education Report #RR-63). Consortium for Policy Research in Education: Philadelphia.

Cossman, G. W. (1969). The effects of a course in science and culture for secondary school students. *Journal of Research in Science Teaching, 6*(3), 274–283.

Cotham, J. C., & Smith, E. L. (1981). Development and validation of the conceptions of scientific theories test. *Journal of Research in Science Teaching, 18*(5), 387–396.

Demirdöğen, B., Hanuscin, D. L., Uzuntiryaki-Kondakci, E., & Köseoğlu, F. (2016). Development and nature of preservice chemistry teachers' pedagogical content knowledge for nature of science. *Research in Science Education, 46*(4), 575–612.

Deng, F., Chen, D. T., Tsai, C. C., & Chai, C. S. (2011). Students' views of the nature of science: A critical review of research. *Science Education, 95*(6), 961–999.

Deniz, H., & Adibelli, E. (2015). Exploring how second grade elementary teachers translate their nature of science views into classroom practice after a graduate level nature of science course. *Research in Science Education, 45*(6), 867–888.

Dibbs, D. R. (1982). *An investigation into the nature and consequences of teachers implicit philosophies of science, Unpublished Doctoral Dissertation*. Birmingham: University of Aston.

Donnelly, L. A., & Argyle, S. (2011). Teachers' willingness to adopt nature of science activities following a physical science professional development. *Journal of Science Teacher Education, 22*(6), 475–490.

Driver, R., Leach, J., Millar, R., & Scott, P. (1996). *Young people's images of science*. Bristol: Open University Press.

Driver, R., Newton, P., & Osborne, J. (2000). Establishing the norms of scientific argumentation in classrooms. *Science Education, 84*, 287–312.

Duit, R., & Treagust, D. F. (2003). Conceptual change: A powerful framework for improving science teaching and learning. *International Journal of Science Education, 25*(6), 671–688.

Duschl, R. A., & Wright, E. (1989). A case-study of high-school teachers decision-making models for planning and teaching science. *Journal of Research in Science Teaching, 26*(6), 467–501.

Duschl, R., Maeng, S., & Sezen, A. (2011). Learning progressions and teaching sequences: A review and analysis. *Studies in Science Education, 47*(2), 123–182.

Eastwood, J. L., Sadler, T. D., Zeidler, D. L., Lewis, A., Amiri, L., & Applebaum, S. (2012). Contextualizing nature of science instruction in socioscientific issues. *International Journal of Science Education, 34*(15), 2289–2315.

Eflin, J. T., Glennan, S., & Reisch, G. (1999). The nature of science: A perspective from the philosophy of science. *Journal of Research in Science Teaching, 36*(1), 107–117.

Einstein, A., & Infeld, L. (1938). *The evolution of physics: From early concepts to relativity and quanta*. New York: Simon & Schuster.

Elby, A., & Hammer, D. (2001). On the substance of a sophisticated epistemology. *Science Education, 85*(5), 554–567.

Erduran, S., & Dagher, Z. R. (2014). *Reconceptualizing the nature of science for science education*. New York: Springer.

Fouad, K. E., Masters, H., & Akerson, V. L. (2015). Using history of science to teach nature of science to elementary students. *Science & Education, 24*(9–10), 1103–1140.

Gallagher, J.J. (1991). Prospective and practicing secondary school science teachers' knowledge and beliefs about the philosophy of science. *Science Education, 75*(1), 121–133.

Gayford, C. (2002). Controversial environmental issues: A case study for the professional development of science teachers. *International Journal of Science Education, 24*(11), 1191–1200.

Gess-Newsome, J. (2002). The use and impact of explicit instruction about the nature of science and science inquiry in an elementary science methods course. *Science & Education, 11*(1), 55–67.

Gill, W. (1977). The editor's page. *The Australian Science Teacher's Journal, 23*, 4.

Gould, S. J. (1977). *Ever since Darwin*. New York: Norton.

Hanuscin, D. L. (2013). Critical incidents in the development of pedagogical content knowledge for teaching the nature of science: A prospective elementary teacher's journey. *Journal of Science Teacher Education, 24*(6), 933–956.

Hanuscin, D. L., Lee, M. H., & Akerson, V. L. (2011). Elementary teachers' pedagogical content knowledge for teaching the nature of science. *Science Education, 95*(1), 145–167.

Harms, H., & Yager, R. E. (1981). *What research says to the science teacher* (Vol. 3). Washington, DC: National Science Teachers Association.

Herman, B. C. (2015). The influence of global warming science views and sociocultural factors on willingness to mitigate global warming. *Science Education, 1*(1), 1–38.

Herman, B. C. (2018). Students' environmental NOS views, compassion, intent, and action: Impact of place-based socioscientific issues instruction. *Journal of Research in Science Teaching, 55*(4), 600–638.

Herman, B. C., & Clough, M. P. (2016). Teachers' longitudinal NOS understanding after having completed a science teacher education program. *International Journal of Science and Mathematics Education, 14*(1), 207–227. https://doi.org/10.1007/s10763-014-9594-1.

Herman, B. C., Clough, M. P., & Olson, J. K. (2013a). Association between experienced teachers' NOS implementation and reform-based science teaching practices. *Journal of Science Teacher Education, 24*(7), 1077–1102.

Herman, B. C., Clough, M. P., & Olson, J. K. (2013b). Teachers' nature of science implementation practices 2–5 years after having completed an intensive science education program. *Science Education, 97*(2), 271–309.

Herman, B. C., Olson, J. K. & Clough, M. P. (2017). The role of informal support networks in teaching the nature of science. *Research in Science Education.* Online first. https://doi.org/10.1007/s11165-016-9610-2

Hodson, D. (1988). Toward a philosophically more valid science curriculum. *Science Education, 72*, 19–40.

Hodson, D. (2008). *Towards scientific literacy: A teachers' guide to the history, philosophy and sociology of science*. Rotterdam: Sense.

Hodson, D. (2009). *Teaching and learning about science: Language, theories, methods, history, traditions and values*. Rotterdam: Sense.

Horizon Research, Inc. (2006). *2005-2006 local systemic change classroom observation protocol.* Available at http://www.horizon-research.com/LSC/manual/

Höttecke, D., & Silva, C. C. (2011). Why implementing history and philosophy in school science education is a challenge: An analysis of obstacles. *Science & Education, 20*(3–4), 293–316.

Howe, E. M., & Rudge, D. W. (2005). Recapitulating the history of sickle-cell anemia research. *Science & Education, 14*(3–5), 423–441.

Irez, S. (2009). Nature of science as depicted in Turkish biology textbooks. *Science Education, 93*(3), 422–447.

Irwin, A. R. (2000). Historical case studies: Teaching the nature of science in context. *Science Education, 84*(1), 5–26.

Khishfe, R. (2012). Nature of science and decision-making. *International Journal of Science Education, 34*(1), 67–100.

Khishfe, R. (2013). Transfer of nature of science understandings into similar contexts: Promises and possibilities of an explicit reflective approach. *International Journal of Science Education, 35*(17), 2928–2953.

Khishfe, R. (2014). Explicit nature of science and argumentation instruction in the context of socioscientific issues: An effect on student learning and transfer. *International Journal of Science Education, 36*(6), 974–1016.

Khishfe, R. (2015). A look into students' retention of acquired nature of science understandings. *International Journal of Science Education, 37*(10), 1639–1667.

Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth graders' views of nature of science. *Journal of Research in Science Teaching, 39*(7), 551–578.

Khishfe, R., & Lederman, N. (2006). Teaching nature of science within a controversial topic: Integrated versus nonintegrated. *Journal of Research in Science Teaching, 43*(4), 395–418.

Kim, S. Y., & Irving, K. E. (2010). History of science as an instructional context: Student learning in genetics and nature of science. *Science & Education, 19*(2), 187–215.

Kimball, M. E. (1967). Understanding the nature of science: A comparison of scientists and science teachers. *Journal of Research in Science Teaching, 5*(2), 110–120.

Kindi, V. (2005). Should science teaching involve the history of science? An assessment of Kuhn's view. *Science & Education, 14*(7–8), 721–731.

King, B. (1991). Beginning teachers' knowledge of and attitude toward history and philosophy of science. *Science Education, 75*, 135–141.

Kolstø, S. D. (2001). 'To trust or not to trust, …' – pupils' ways of judging information encountered in a socio-scientific issue. *International Journal of Science Education, 23*(9), 877–901.

Kolstø, S. D. (2008). Science education for democratic citizenship through the use of the history of science. *Science & Education, 17*(8–9), 977–997.

Kruse, J. W., Easter, J. M., Edgerly, H. S., Seebach, C., & Patel, N. (2017). The impact of a course on nature of science pedagogical views and rationales. *Science & Education, 26*(6), 613–636.

Lakin, S., & Wellington, J. (1994). Who will teach the nature of science? Teachers' views of science and their implications for science education. *International Journal of Science Education, 16*(2), 175–190.

Lederman, N. G. (1992). Students' and teachers' conceptions of the nature of science: A review of the research. *Journal of Research in Science Teaching, 29*(4), 331–359.

Lederman, N. G. (1999). Teachers' understanding of the nature of science and classroom practice: Factors that facilitate or impede the relationship. *Journal of Research in Science Teaching, 36*(8), 916–929.

Lederman, N. G. (2006). Syntax of nature of science within inquiry and science instruction. In L. B. Flick & N. G. Lederman (Eds.), *Scientific inquiry and nature of science: Implications for teaching, learning, and teacher education*. Dordrecht: Springer.

Lederman, N. G. (2007). Nature of science: Past, present and future. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 831–879). Mahwah: Lawrence Erlbaum.

Lederman, N. G., & O'Malley, M. (1990). Students' perceptions of tentativeness in science: Development, use, and sources of change. *Science Education, 74*(2), 225–239.

Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., & Schwartz, R. S. (2002). Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching, 39*(6), 497–521.

Lederman, N. G., Bartos, S. A., & Lederman, J. S. (2014). The development, use, and interpretation of nature of science assessments. In *International handbook of research in history, philosophy and science teaching* (pp. 971–997). Dordrecht: Springer.

Lee, H., & Witz, K. G. (2009). Science teachers' inspiration for teaching socio-scientific issues: Disconnection with reform efforts. *International Journal of Science Education, 31*(7), 931–960.

Leung, J. S. C., Wong, A. S. L., & Yung, B. H. W. (2015). Understandings of nature of science and multiple perspective evaluation of science news by non-science majors. *Science & Education, 24*(7–8), 887–912.

Liang, L. L., Chen, S., Chen, X., Kaya, O. N., Adams, A. D., Macklin, M., & Ebenezer, J. (2008). Assessing preservice elementary teachers' views on the nature of scientific knowledge: A dual-response instrument. *Asia-Pacific Forum on Science Learning and Teaching, 9*(1), 1–20. http://www.ied.edu.hk/apfslt/.

Lin, H. S., & Chen, C. C. (2002). Promoting preservice chemistry teachers' understanding about the nature of science through history. *Journal of Research in Science Teaching, 39*(9), 773–792.

Lin, S. F., Lieu, S. C., Chen, S., Huang, M. T., & Chang, W. H. (2012). Affording explicit-reflective science teaching by using an educative teachers' guide. *International Journal of Science Education, 34*(7), 999–1026.

Loving, C. (1991). The scientific theory profile: A philosophy of science model for science teachers. *Journal of Research in Science Teaching, 28*, 823–838.

Manuel, D. E. (1981). Reflections on the role of history and philosophy of science in school science education. *School Science Review, 62*, 769–771.

Martin, M. R. (1972). *Concepts of science education: A philosophical analysis*. Greenview: Scott, Foresman.

Matkins, J. J., & Bell, R. L. (2007). Awakening the scientist inside: Global climate change and the nature of science in an elementary science methods course. *Journal of Science Teacher Education, 18*, 137–163.

Matthews, M. R. (1989). A role for history and philosophy in science teaching. *Interchange, 20*, 3–15.

Matthews, M. R. (1994). *Science teaching: The role of history and philosophy of science*. New York: Routledge.

Matthews, M. (2012). Changing the focus: From nature of science (NOS) to features of science (FOS). Chapter 1. In M. S. Khine (Ed.), *Advances in nature of science research: Concepts and methodologies*. Dordrecht: Springer.

Matthews, M. R. (2015). *Science teaching: The role of history and philosophy of science* (2nd ed.). New York: Routledge.

McComas, W. F. (2010). The history of science and the future of science education: A typology of approaches to the history of science in science instruction. In P. V. Kokkotas, K. S. Malamitsa, & A. A. Rizaki (Eds.), *Adapting historical knowledge production to the classroom* (pp. 37–54). Rotterdam: Sense.

McComas, W. F., & Kampourakis, K. (2015). Using the history of biology, chemistry, geology and physics to teach aspects of the nature of science. *Review of Science, Mathematics and ICT (Information and Communication Technology) Education, 9*(1), 47–76.

McComas, W. F., & Nouri, N. (2016). The nature of science and the next generation science standards: Analysis and critique. *Journal of Science Teacher Education, 27*(5), 555–576.

McComas, W. F., & Olson, J. K. (1998). The nature of science in international science education standards documents. Chapter 2. In W. F. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 41–52). Boston: Kluwer/Springer.

McDonald, C. V. (2010). The influence of explicit nature of science and argumentation instruction on preservice primary teachers' views of nature of science. *Journal of Research in Science Teaching, 47*(9), 1137–1164.

Medawar, P. B. (1963). Is the scientific paper a fraud? *Listener, 70*, 377–378.

Medawar, P. B. (1990). *The threat and the glory: Reflections on science and scientists*. New York: HarperCollins.

Morrison, J. A., Raab, F., & Ingram, D. (2009). Factors influencing elementary and secondary teachers' views on the nature of science. *Journal of Research in Science Teaching, 46*(4), 384–403.

Moss, D. M., Abrams, E. D., & Robb, J. (2001). Examining student conceptions of the nature of science. *International Journal of Science Education, 23*(8), 771–790.

Munby, H. (1982). The place of teachers' beliefs in research on teacher thinking and decision making, and an alternative methodology. *Instructional Science, 11*, 201–225.

National Research Council. (1996). *National science education standards*. Washington, DC: National Academies Press.

National Science Teachers Association. (2012). *NSTA preservice science standards.* https://www.nsta.org/preservice/docs/2012NSTAPreserviceScienceStandards.pdf

NGSS Lead States. (2013). *Next generation science standards: For states, by states*. Washington, DC: National Academies Press.

Nunan, E. (1977). History and philosophy of science and science teaching: A revisit. *The Australian Science Teachers' Journal, 23*, 65–71.

Olson, J. K. (2018). The inclusion of the nature of science in nine recent international science education standards documents. *Science & Education*. https://doi.org/10.1007/s11191-018-9993-8.

Osborne, J. (2010). Arguing to learn in science: The role of collaborative, critical discourse. *Science, 328*, 463–466.

Pagliarini, C. D. R., & Silva, C. C. (2007, March). History and nature of science in Brazilian physics textbooks: Some findings and perspectives. In *Ninth International History, Philosophy, Sociology & Science Teaching Conference (IHPST), Calgary, Canada* (pp. 28–31). Calgary: IHPST.

Paraskevopoulou, E., & Koliopoulos, D. (2011). Teaching the nature of science through the Millikan-Ehrenhaft dispute. *Science & Education, 20*(10), 943–960.

Pomeroy, D. (1993). Implications of teachers' beliefs about the nature of science: Comparison of the beliefs of the scientists, secondary science teachers, and elementary teachers. *Science Education, 77*(3), 261–278.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*(2), 211–227.

Price, R. M., & Perez, K. E. (2018). Many paths toward discovery: A module for teaching how science works. *Journal of College Science Teaching, 47*(3), 78–87.

Quigley, C., Pongsanon, K., & Akerson, V. (2010). If we teach them, they can learn: Young students views of nature of science aspects to early elementary students during an informal science education program. *Journal of Science Teacher Education, 21*(7), 887–907.

Ramsey, G. A., & Howe, R. W. (1969). An analysis of research on instructional procedures in secondary school science: Part I—outcomes of instruction. *The Science Teacher, 36*(3), 62–70.

Robinson, J. T. (1969). Philosophy of science: Implications for teacher education. *Journal of Research in Science Teaching, 6*, 99–104.

Rubba, P. A. (1976). *Nature of scientific knowledge scale*. Bloomington: School of Education, Indiana University.

Rudge, D. W., Cassidy, D. P., Fulford, J. M., & Howe, E. M. (2014). Changes observed in views of nature of science during a historically based unit. *Science & Education, 23*(9), 1879–1909.

Rudolph, J. L. (2000). Reconsidering the "nature of science" as a curriculum component. *Journal of Curriculum Studies, 32*(3), 403–419.

Sadler, T. D., & Zeidler, D. L. (2005). Patterns of informal reasoning in the context of socioscientific decision making. *Journal of Research in Science Teaching, 42*(1), 112–138.

Sadler, T. D., Chambers, W. F., & Zeidler, D. (2002). *Investigating the crossroads of socioscientific issues, the nature of science, and critical thinking*. Paper presented at the annual meeting of the National Association for Research in Science Teaching, New Orleans, LA.

Sadler, T. D., Chambers, W. F., & Zeidler, D. L. (2004). Student conceptualizations of the nature of science in response to a socioscientific issue. *International Journal of Science Education, 26*, 387–409.

Sandoval, W. A. (2003). The inquiry paradox: Why doing science doesn't necessarily change ideas about science. In C. P. Constantinou & Z. C. Zacharia (Eds.), *Proceedings of the Sixth International Computer-Based Learning in Science Conference 2003* (pp. 825–834). Nicosia: Lawrence Erlbaum.

Schalk, K. A. (2012). A socioscientific curriculum facilitating the development of distal and proximal NOS conceptualizations. *International Journal of Science Education, 34*(1), 1–24.

Scharmann, L. C., Smith, M. U., James, M. C., & Jensen, M. (2005). Explicit reflective nature of science instruction: Evolution, intelligent design, and umbrellaology. *Journal of Science Teacher Education, 16*(1), 27–41.

Schwartz, R. S., & Lederman, N. G. (2002). "It's the nature of the beast": The influence of knowledge and intentions on learning and teaching nature of science. *Journal of Research in Science Teaching, 39*(3), 205–236.

Schwartz, R. S., & Lederman, N. G. (2008). What scientists say: Scientists' views of nature of science and relation to science context. *International Journal of Science Education, 30*(6), 727–771.

Schwartz, R. S., Lederman, N. G., & Crawford, B. A. (2004). Developing views of nature of science in an authentic context: An explicit approach to bridging the gap between nature of science and scientific inquiry. *Science Education, 88*(4), 610–645.

Sismondo, S. (2004). *An introduction to science and technology studies*. Malden: Blackwell.

Smith, C. L., & Wiser, M. (2015). On the importance of epistemology–Disciplinary core concept interactions in learning progressions. *Science Education, 99*(3), 417–423.

Stake, R. E., & Easley, J. A. (1978). *Case studies in science education*. Urbana-Champaign: University of Illinois. http://files.eric.ed.gov/fulltext/ED166059.pdf.

Strike, K. A., & Posner, G. J. (1992). A revisionist theory of conceptual change. In R. Duschl & R. J. Hamilton (Eds.), *Philosophy of science, cognitive psychology and educational theory and practice* (pp. 147–176). Albany: State University of New York Press.

Summers, M. (1982). Philosophy of science in the science teacher education curriculum. *European Journal of Science Education, 4*, 19–27.

Sweeney, S. J. (2010). *Factors affecting early elementary (K-4) teachers' introduction to the nature of science: A national survey*. Unpublished doctoral dissertation. University of Arkansas, Fayetteville, AR.

Tao, P. K. (2003). Eliciting and developing junior secondary students' understanding of the nature of science through a peer collaboration instruction in science stories. *International Journal of Science Education, 25*(2), 147–171.

Toulmin, S. (1958). *The uses of argument*. Cambridge: Cambridge University Press.

Wahbeh, N., & Abd-El-Khalick, F. (2014). Revisiting the translation of nature of science understandings into instructional practice: Teachers' nature of science pedagogical content knowledge. *International Journal of Science Education, 36*(3), 425–466.

Walker, K. A., & Zeidler, D. L. (2004). *The role of students' understanding of the nature of science in a debate activity: Is there one?* Paper Presented at the Annual Meeting of the National Association for Research in Science Teaching (NARST), Vancouver, BC, Canada.

Waters-Adams, S. (2006). The relationship between understanding of the nature of science and practice: The influence of teachers' beliefs about education, teaching and learning. *International Journal of Science Education, 28*(8), 919–944.

Watson, J. (1968). *The double helix*. New York: Atheneum.

Watson, J., & Crick, F. (1953). A structure for deoxyribose nucleic acid. *Nature, 171*, 737–738.

Weiss, I. R. (1993). Science teachers rely on the textbook. In R. E. Yager (Ed.), *What research says to the science teacher, vol. 7: The science, technology, society movement*. Washington, DC: National Science Teachers Association.

Weiss, I. R., Pasley, J. D., Smith, P. S., Banilower, E. R., & Heck, D. J. (2003). *Looking inside the classroom: A study of K–12 mathematics and science education in the United States*. Chapel Hill: Horizon Research.

Welch, W. W. (1966). *Welch science process inventory, form D*. Minneapolis: Minnesota Research and Evaluation Center, University of Minnesota.

Wessel, M. R. (1980). *Science and conscience*. New York: Columbia University Press.

Williams, C. T., & Rudge, D. W. (2016). Emphasizing the history of genetics in an explicit and reflective approach to teaching the nature of science. *Science & Education, 25*(3–4), 407–427.

Wong, S. L., Hodson, D., Kwan, J., & Yung, B. H. W. (2008). Turning crisis into opportunity: Enhancing student-teachers' understanding of nature of science and scientific inquiry through a case study of the scientific research in severe acute respiratory syndrome. *International Journal of Science Education, 30*(11), 1417–1439.

Yerrick, R. K. (2000). Lower track science students' argumentation and open inquiry instruction. *Journal of Research in Science Teaching, 37*(8), 807–838.

Zeidler, D. L., Walker, K. A., Ackett, W. A., & Simmons, M. L. (2002). Tangled up in views: Beliefs in the nature of science and responses to socioscientific dilemmas. *Science Education, 86*, 343–367.

Zeidler, D. L., Sadler, T. D., Simmins, M. L., & Howes, E. V. (2005). Beyond STS: A research-based framework for socioscientific issues education. *Science Education, 89*(3), 357–377.

Zeidler, D. L., Herman, B. C., Ruzek, M., Linder, A., & Lin, S. S. (2013). Cross-cultural epistemological orientations to socioscientific issues. *Journal of Research in Science Teaching, 50*(3), 251–283.

Zohar, A., & Nemet, F. (2002). Fostering students' knowledge and argumentation skills through dilemmas in human genetics. *Journal of Research in Science Teaching, 39*, 35–62.

Part II

Nature of Science Instruction: Foundation Knowledge for Nature of Science Instruction

Chapter 5
Beyond Experiments: Considering the Range of Investigative and Data-Collection Methods in Science

Sandra Sturdivant West, Susan Schwinning, and Alexis D. Denn

5.1 Introduction

This chapter provides an overview of the variety of methods available that scientists have developed to explore the natural and material world. Each method is accompanied by discussion of a rich set of procedures that extend beyond just experiments that many believe to be *the* way that science works. This limited view of scientific research is frequently found in classroom discussions, textbooks, lab manuals, professional development plans, online resources, posters hanging on classroom walls, state science standards, and even implied by the requirements found in many science competitions. To counter this pervasive misconception, this chapter offers a more complete illustration of the *ways* that investigations may occur in science by providing a detailed overview of all scientific methodology in a useful tool we call the "Modes of Scientific Inquiry" (MSI) flowchart (Fig. 5.1). This chart provides examples of qualitative and quantitative methods, observational attributes, useful analytical approaches, and possible graphical representations of results from such investigations. Science teachers, other formal and informal science educators and students will find this overview useful in discussions about how science works and, more importantly, in conducting authentic scientific research.

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_5

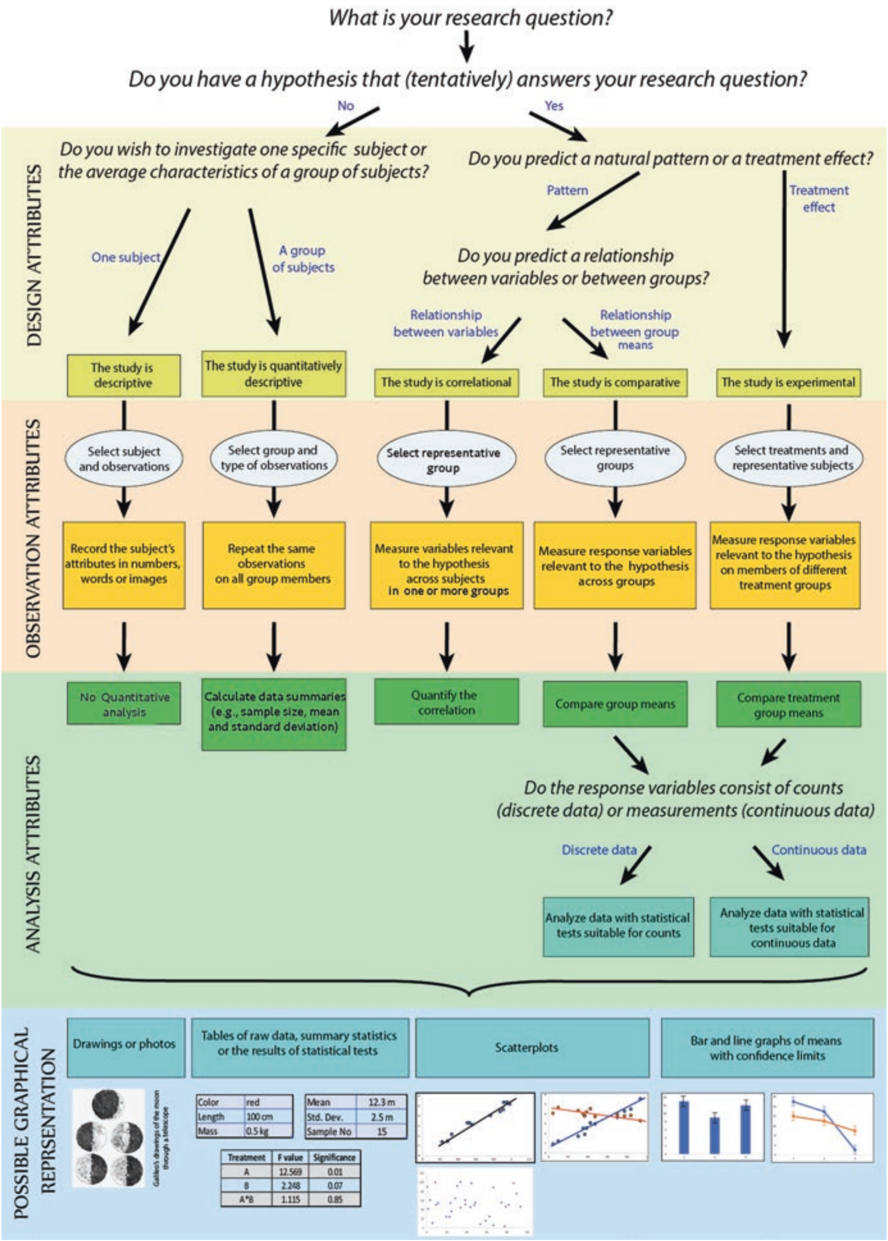

Fig. 5.1 Modes of scientific inquiry (MSI) flowchart

5.2 How the Modes of Scientific Inquiry (MSI) Flowchart Can Be Useful

The MSI tool provides explicit and specific illustrations of the various ways that scientists develop an understanding of the natural and material world. The MSI shows that legitimate and useful empirical data may be gained through both experimental and nonexperimental means, depending on the question that is being asked. Even with the frequent advocacy for investigation-based science teaching, students are typically directed to conduct investigations with little or no explicit instruction on how to create a research question and how to plan an investigation to answer that research question through the collection of relevant data. Not surprisingly, students commonly propose some version of a classic *experiment*al design with control and test settings. Experiments with a control often may be considered the "gold standard" in science, but they are not the only way that scientists can reliably obtain useful information. The new U.S. science standards as discussed in *A Framework for K-12 Science Education* (NRC 2012), which led to the standards themselves released as the Next Generation Science Standards (NGSS Lead States 2013), identify three types of scientific investigations: Observational (Descriptive), Correlational, and Experimental. While this is an improvement over more limited discussions of scientific methodology, these various investigations are not clearly explained nor are the distinctions between Correlational and Comparative mentioned. The MSI is designed to address this missing information and, as such, provide a more complete view of data collection available to scientists and science students alike.

5.3 Teaching with Inquiry and Teaching How Science Functions

What does inquiry in science look like? People have always had questions about their world and knowledge-seekers have developed diverse inquisitive paths: some artistic, religious, social science, or scientific. However, the nature of *scientific* inquiry is captured well in a quote from the *Log from the Sea of Cortez* (Steinbeck 1986) where the biologist replies to the local who asks "Then, what do you search for? … We search for something that will seem like truth to us; understand that principle which keys us deeply into the pattern of all life; the relations of things, one to another."

In the broadest sense, science focuses on investigating and reaching conclusions about patterns in the natural or material world, using any method appropriate for the task. Methods range from immediately practical such as quantifying correlations between human behaviors and health risks, to documenting the curious and unexpected, to the systematic, incremental testing of far-reaching explanatory models. All these modes of investigation are profoundly important. For example, the mere observation of a correlation between high salt intake and higher blood pressure or between smoking and lung cancer, without any explanation of cause, can nevertheless suggest appropriate health precautions. Governmental laws limiting tobacco sales to minors were created from experimental findings that identified smoking as a cause of lung cancer. Other observations are singular and seem to have no practical application at the time. For example, a chemist in the eighteenth century, interested only in describing the characteristics of mineral rocks discovered uranium, which led to the discovery of radioactivity.

To help students gain this more-complete understanding of the ways in which science works at the basic level, we offer a novel resource that encapsulates different modes of scientific investigation. We developed the resource with the notion to illustrate the diverse aims and strategies underlying authentic scientific investigations and introduce it here to provide guidance and spark a conversation about this important topic.

5.4 Using the MSI to Guide the Conduct of Scientific Investigations

The MSI is a flowchart (Fig. 5.1) to guide both teachers and students through the phases of conducting a scientific investigation using various modes of data collection and associated analysis. It starts with the recognition of the research question and the identification of a research target (a subject or subjects, a pattern or a process?) and then moves on to the kinds of data that will be collected and how those data will be analyzed. In addition, we have created the *Attributes of Scientific Investigations* table (Table 5.1) that provides further clarification of the investigative attributes from different perspectives. Both the MSI flowchart and *Attributes of Scientific Investigations* table serve to outline the design similarities and differences in the major types of inquiry, in terms of explicit design, observation, and analysis attributes of any scientific investigation. We also highlighted various options for communicating the results of a scientific investigation in photos, drawings, tables, or graphs.

In the following section, we will consider case examples to demonstrate how to navigate the MSI flowchart and *Attributes of Scientific Investigations* table each linked to a specific kind of research question.

Table 5.1 Attributes of scientific investigations

		Type of investigation			
	Attributes of scientific investigations	Descriptive/quantitatively descriptive	Correlational	Comparative	Experimental
Design attributes	**Questions about attributes**				
	Does the investigator have a hypothesis?		Yes	Yes	Yes
	Is the investigator interested in learning only about one specific subject or similarities within a group of subjects?	Yes			
	Is the investigator interested in learning about patterns or processes?		Yes	Yes	Yes
	Does the investigator change (interfere with) anything in the environment (i.e., impose treatments) to gain knowledge?				Yes
	Does the investigator include a “control treatment” (i.e., an experimental group for which certain treatments are omitted)?				Yes
	Will the investigator impose specific changes or constraints (treatments) on the subjects(s) of the investigation?				Yes
Observation attributes	Relevant qualitative/accidental/incidental/opportunistic observations	Yes	Yes	Yes	Yes
	Does the investigation focus on making separate observations in different places, at different times, or on different kinds of subjects?			Yes	Yes
	Does the investigation focus on observing different variables on the same subjects?		Yes		Perhaps
	Does the investigation require repeated observations (replication)?	Perhaps[a]	Yes	Yes	Yes
	Observations of the same variables across groups or treatments			Yes	Yes

(continued)

Table 5.1 (continued)

		Type of investigation			
	Attributes of scientific investigations	Descriptive/quantitatively descriptive	Correlational	Comparative	Experimental
Analysis attributes	Does the investigator calculate means, medians, frequencies, and measures of variation?	Perhaps[a]	Yes	Yes	Yes
	Does the investigator characterize relationships between variables?		Yes		Perhaps[b]
	Does the investigator characterize similarities or differences between groups?		Perhaps[b]	Yes	Yes
	Does the investigator highlight treatment effects by comparing the outcome of a treatment with a control?				Yes
	Does the investigator fit observed data to statistical models (Correlation, Regression, ANOVA, ANCOVA) to illustrate quantitative relationships between variables or treatment effects?		Yes	Yes	Yes
	Fitting statistical models to determine the effects of independent treatment factors on dependent (response) variables				Yes
	Can/should the investigator use photos or drawings to communicate results of the investigation?	Perhaps	Perhaps	Perhaps	Perhaps
Possible graphical/visual representations	Should the investigator compose tables of raw data to communicate results?	Yes[c]			
	Can the investigator compose tables of group or treatment means and measures of variation?			Yes	Yes
	Can the investigator compose tables summarizing the results of statistical tests and methods?		Yes	Yes	Yes
	Can the investigator draw bar or line graphs to illustrate results?		Yes	Yes	Yes
	Can the investigator draw scatterplots with fitted lines or curves?		Yes	Perhaps[b]	Perhaps[b]

Possible conclusion attributes	Should the investigator report relevant qualitative observations that help to explain or enhance results?	Yes	Yes	Yes	Yes
	Report of quantitative findings	Perhaps	Yes	Yes	Yes
	Can the investigator state conclusions supported by statistical analyses?		Yes	Yes	Yes
	Tentative assessment of the study based on planned and unplanned observations, statistical		Yes		Yes

[a] Engaging in repeated observations and the further calculation of means is not possible when there is only one subject to investigate

[b] Investigations can combine several methods, for example, an experiment or a comparative study may also involve the measurement of relationships between variables

[c] Raw data are usually not included in a scientific report, since the purpose of a report is to summarize and organize information, *unless* the investigation focusses on a singular subject, such as a one-of-a-kind fossil

5.5 Example 1: A Qualitative Descriptive Investigation

Research Question: This simple investigation is motivated by noticing a bird at the window. An investigator might want to know more about the bird than what can be gleamed in the moment and ask "What exactly does the bird look like (how big is it, what is its shape, what color are its feathers?)."

A short version of research question would be "What are the external characteristics of the bird that visits a bird feeder placed in view of our classroom window?"

Hypothesis: After formulating the research question, then determine if the investigation will have a hypothesis (based on a theory or a model) that (tentatively) answers your research question. This simple research question assumes no model or theory-based prior knowledge and therefore there is nothing on which to base a hypothesis (NRC 2012, p. 60). The lack of a hypothesis in the investigation design indicates that the investigation design will fall into the category of "Nonexperimental/Descriptive/Observational."

Design Attributes: The next question is "Do you wish to investigate one specific subject or the average characteristics of a group of subjects?" This research investigates "a single subject," that is, the individual bird visiting the window. This means the investigation is more specifically classified as "Qualitatively Descriptive."

Observation Attributes: Attributes or characteristics observed can include words, images, or numbers. The subject is a bird and the characteristics that we want to observe and record could include the color of the feathers, shade of red of the feathers, color of the beak, color of the legs, and and/or feet, any unusual feature such as a crest of feathers on top of the head, approximate body size or height, and approximate length of legs.

Analysis Attributes: There are no numerical data analysis or descriptive statistics (mean, range, median, and mode) possible since the study involves only one subject (one bird). However, numerical data may be obtained such as the approximate body size or height, but there is no data analysis.

Possible Graphical Representation: This study could include drawings of the bird, pictures taken by students or teacher, a table of the attributes or pictograph/pictogram.

Note that in the *Attributes of scientific inquiry* (Table 5.1) the information can be used in a Descriptive study (Ex. 1), which indicates that observations can be made on the "bird" at different times of day and from separate sites such as outside the classroom and not just from inside the classroom. Also, "Tables of raw data" on the *Attributes of scientific inquiry* (Table 5.1) indicates that both the Descriptive and Quantitative Descriptive studies can have raw data tables. The Descriptive study could have a data table recording the height of the bird, but no data can be analyzed since the study involves only one subject (a bird).

5.6 Example 2: A Quantitative Descriptive Investigation

Research Question: The motivating question is 'how much water is lost in a day from a leaky faucet?'. After discussion, the students narrow this question down to the research question: 'How much water is in a drop of water?' Together with information from their investigation on the drip rate, they can calculate the answer for the original, motivating question.

Hypothesis: There is no prior expectation as to how much water is in a drop of water, so no hypothesis is developed.

Design Attributes: The subject of this investigation is a water droplet. However, the students recognize that they should measure not just one droplet (= a single subject), since droplet size may vary. They decide to measure many droplets (= a group of subjects) and calculate a mean droplet size. Since the same measurement is repeated on several subjects, the study is quantitatively descriptive.

Observation Attributes: Students select the classroom faucet to provide droplets for this investigation, by setting the faucet to drip a little bit. They decide to collect one droplet at a time into a small plastic tray to measure weight. They repeat this weight observation for 20 droplets.

Analysis Attributes: From the 20 quantitative observations they collected, students calculate a mean droplet size.

Graphical Representation: The students develop a table that shows for several drip rates (e.g., 1 per minute to 60 drips per minute), how many drops fall in a 24-hour period and how many liters of water this adds up to.

Note: In this particular example, the calculation of a standard deviation is not essential to answering the research question, but could be calculated to determine how much droplet sizes vary. The reasons for relatively small variation can be discussed in terms of surface tension determining when a droplet is large enough to break off.

5.7 Example 3: A Correlational Investigation

Research Question: This investigation is motivated by observing different leaf shapes in nature and asking how variation from round to more elongated leaf shapes could be quantified. The students might want to know "What is the relationship between leaf length and width for leaves of a particular species of tree in a particular area?" Specifically, the research question is: "Is there a relationship between longest leaf length (L) and widest leaf width (W) that remains fixed for leaves on a tree or shrub even as leaf sizes vary?"

Hypothesis: Since the students have a very specific question in mind, they can formulate a tentative hypothesis: "For leaves on the same tree or shrub, W will be proportional to L." Furthermore, they might speculate based on understanding of geometry that “in rounder leaves, the proportion W:L will be closer to 1:1, and in elongated leaves, less than that.”

Design Attributes: The hypothesis implies that multiple repeated observations will be conducted on the same kind of subjects (i.e., multiple leaves from the same tree); therefore, the study is quantitative. In addition, two variables will be measured (W and L) on every subject. Since the focus of the investigation is the relationship between these two variables, the study is correlational.

Observation Attributes: The students select the trees or shrubs to be included in the investigation. They collect multiple leaves (e.g., 10) from each species across a leaf size range, measure L and W and record the data in a table.

Analysis Attributes: Students perform a regression analysis separately for each species with L on the y-axis and W on the x-axis to determine if L and W are linearly related to each other. If so, this confirms the first hypothesis. Secondly, they compare the slopes derived for different species and evaluate the second hypotheses, that more elongated leaves should have lower slope ($\Delta W/\Delta L$) values.

Possible Graphical Representations: Students can show scatter graphs for each species with regression lines drawn over them. Alongside (or integrated into the graphs), students can show representative silhouettes of the leaf shape associated with each species.

5.8 Conclusions and Recommendations

This chapter is written to enable users to better understand inquiry in the scientific enterprise. The search for scientific knowledge is found in ancient philosophical writings with descriptions of the “what” patterns observed in natural or material world and possible reasons of “why” those patterns occurred in nature. Moreover, careful consideration is given to the range of users from the elementary student to the Kindergarten teacher to the high school science teacher to university faculty.

Scientific inquiry almost always begins with an observation followed by a question in the mind of the investigator. This pattern is typical whether the age is preschool or adult. Therefore, the *MSI* flowchart begins with examining the initial question and from this starting point guides the investigator through suitable methods of study design, data collection, and analysis. Crucially, the *MSI* and the *Attributes of Scientific Investigations* are consistent with long-standing standards of scientific inquiry as documented in international professional and scientific publications.

To practice using the *MSI*, think of a question you might have now or had in the past about a natural phenomenon. How much evidenced-based information do you or someone else have about the subject of the question? If little or nothing is known, then the phenomenon or object of interest probably needs to be described in a type of *Descriptive Investigation*. Or, if the subject of the investigation itself is already well known, perhaps there are open questions about the relationships of that subject in the world. In this case, a testable hypothesis can be created about such relationships and investigated in a *Correlational* or *Comparative Investigation*. Investigations can have both attributes, as in our third example, in which the *correlation* between leaf length and width was *compared* between species.

In some instances, you (the investigator) can take a more active role by testing the subject's responses to specific factors or circumstances that you create and maintain control. The purpose of such an *Experimental Investigation* is to determine the relationship between cause (i.e., the specific factors and circumstances you impose) and the effects it has on the experimental subjects. A C*ontrol* is often part of such a design, usually as the experimental group for which a specific causal factor is omitted. If measured effects are statistically different between a treatment group and a control group, one can confidently conclude that the factor or factors *caused* the difference in the subjects.

As you practice navigating the *MSI* flowchart the *Attributes of Scientific Investigations*, you will begin to better understand the versatility of methods available for scientific investigation and perhaps experience the excitement of designing a clever investigation that could answer your scientific question(s). We view the *MSI* flowchart and the *Attributes of Scientific Investigations* as developing documents and welcome your comments.

References

National Research Council. (2012). *A framework for K–12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: National Academies Press.

NGSS Lead States. (2013). *Next generation science standards: For states, by states*. Washington, DC: National Academies Press.

Steinbeck, J. (1986). *The log from the Sea of Cortez: The narrative portion of the book, Sea of Cortez,* by John Steinbeck and E.F. Ricketts, 1941, reissued with a profile "About Ed Ricketts". New York: Penguin Books.

Chapter 6
Exchanging the Myth of a Step-by-Step Scientific Method for a More Authentic Description of Inquiry in Practice

Rebecca Reiff-Cox

The National Science Education Standards (NSES) describes scientific inquiry as "the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work" (NRC 1996, p. 23). This emphasis on diverse ways is infrequently depicted in science textbooks which tend to emphasize a single scientific method to describe scientific inquiries (Anderson 2002; Sterner 1998; Bauer 1992; Conant 1947). One of the most prevalent myths about science is scientists use a single method to solve problems (Lederman 1998; McComas 1996; Bauer 1992; Duschl 1990; Conant 1947). There is some utility in discussing the single scientific method to identify the steps and characteristics of scientific investigations but this one-size-fit all model does not accurately reflect the diverse approaches that real-world scientists take when conducting investigations. This chapter will focus on the myth and reality of the scientific method so that science teachers can better provide students with accurate views on how scientists contribute to the scientific knowledge base. Before discussing the reality of the scientific method, it will be useful to examine how textbooks often portray knowledge production in science.

6.1 The Myth and Reality of the Scientific Method

The traditional step-by-step scientific method often included in textbooks as the school science version of scientific inquiry typically lists the following steps: (1) recognition of a problem, (2) collection of relevant data, (3) formulation of hypoth-

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_6

eses, (4) testing of hypothesis, and (5) drawing conclusions (Dressel et al. 1960). Certainly these events or steps do occur as scientists generate knowledge, but as Cooper 2002; Lederman 1998; McComas 1996; and many others have pointed out, a stepwise model for inquiry is not reflective of how real science is conducted and using this model, therefore, fails to portray accurately the lively and diverse processes scientists use in approaching their investigations.

The scientific method is not a recipe with measurements to take and procedures to follow (Sterner 1998; Bauer 1992; NSSE 1960; Conant 1947). Scientists' descriptions of their research processes (Cooper 2002; Gibbs and Lawson 1992; Bauer 1992; Holton 1988; Keller 1983; Feyerabend 1975; Bridgman 1955; Beveridge 1957; Conant 1947) coincide with the statement from *Science for All Americans:* "There is simply no fixed set of steps that scientists follow, no one path that leads them unerringly to scientific knowledge. There are, however, certain features of science that give its distinctive character as a mode of inquiry" (AAAS 1990, p. 4).

Therefore, a contradiction exists between the private practices of science and those portrayed to the public. So infused is the public version of science in the current culture that textbooks typically just present the stepwise scientific method as the single arbiter of progress. Most scientists know the structure of an investigation is not so sequential and rigid (Ziman 1984). However, the public is not exposed to the "months of tortuous, wasteful effort [that] may be hidden behind a few elegant paragraphs, with the sequence of presented development running directly opposite to the actual chronology, to the confusion of the students and historians alike" (Holton 1988, p. 406). Typically the format of scientific papers is prescribed and results appear to flow neatly out of the procedures, closely resembling established principles of the scientific method (Medawar 1963; Beveridge 1957).

Even though this one-sided portrayal of science as a collection of products is sharply criticized by scientists (Holton 1988; Schwab 1962; Conant 1947), textbooks and even scientific articles themselves do not often reveal the actual paths to discovery (Duschl 1985, 1990; Schwab 1962). In reality, practicing scientists use a variety of pathways to approach a problem, formulate hypotheses, or make relationships in the data (Roberts 1989; McClintock and Keller 1983; Goodfield 1981; Brush 1974, 1976; Holton 1964, 1988; Beveridge 1957; Bridgman 1955; Conant 1947).

Physicist Gerald Holton (1988) describes the science-in-the-making approach characterized by circuitous paths, unexpected findings, and false starts as private science or the *context of discovery* side of science. During the context of discovery scientific attributes of creativity, curiosity, intuition, and subjectivity are valued in selecting problems of study, framing investigations, and studying relationships in the data (Medawar 1963). This context of discovery is an essential component of science but is usually kept *private*.

In order to understand progress in science, the elements of discovery just mentioned must be included, but school science often shows only public science or the *context of justification* as typified by concepts that have been scrutinized or "dry-cleaned" to wash out signs of intellectual struggle (Holton 1988, p. 9). Textbooks reflect this public science by including the scientific method as the sterilized version of scientific progress. Hence, the public is more familiar with the context of the justification side of science whereas the context of discovery side has been neglected, forgotten, and devalued, as evident by its scarcity in science textbooks (Bauer 1992; Gibbs and Lawson 1992; Brush 1976; Medawar 1963).

The cornerstone of this inquiry process is built on the context of discovery and justification. During the context of discovery phase, scientists use their intuition, imagination, and creativity to gather information, generate ideas, connect knowledge, and frame investigations. At the frontier, scientists do not follow a linear paved road leading to the finish line. Scientists vary in the paths they take to explore their inquiries but they keep track of their journey, recording unexpected findings, landmarks, and ideas.

At the frontier of science, the scientist stands between the known and the unknown and may not have a clear direction of where to proceed or what to look for but the scientist maintains persistence and an open mind when exploring new terrain. In this context of discovery phase, scientists may see new patterns, take time to reflect on the data, try out different approaches, ask many questions, or use one's experience to relate to new findings. At this stage, the scientist may be unclear of the interacting agents, the cause of the phenomenon, or if any relationship exists (Goodfield 1981). The scientist is not attached to a particular hypothesis but is open to contradictory results, new discoveries, or the possibility of starting on a new course. Giving students the chance to explore materials and ideas has been well documented (Bybee 1997; Hawkins 1965) but explicit instruction should also include instances where scientists from all disciplines have used exploratory processes to advance the scientific knowledge base.

The need becomes to recognize the limitations of current representations of the scientific method and to generate a fluid, more dynamic model for capturing the creative, private, and messy side of science.

6.2 The Inquiry Wheel: An Alternative Description of the Stepwise Scientific Method

In an attempt to bring research science faculty into discussions about scientific inquiry, science educators Reiff et al. (2002) interviewed 52 scientists from biology, environmental science, chemistry, medical sciences, physics, and geology about their conceptions of scientific inquiry. Questions included how these scientists approach and conduct scientific investigations, what the stages are of a typical scientific inquiry, and what characteristics are seen when scientists engage in inquiry. Results of these interviews resulted in the development of a theoretical model called the "inquiry wheel" to portray more accurately scientists' conceptions of scientific inquiry and their journeys (Reiff 2004, see Fig. 6.1).

The inquiry wheel does not attempt to represent the viewpoint of each scientist nor from the perspective of a particular discipline but instead is a model built from

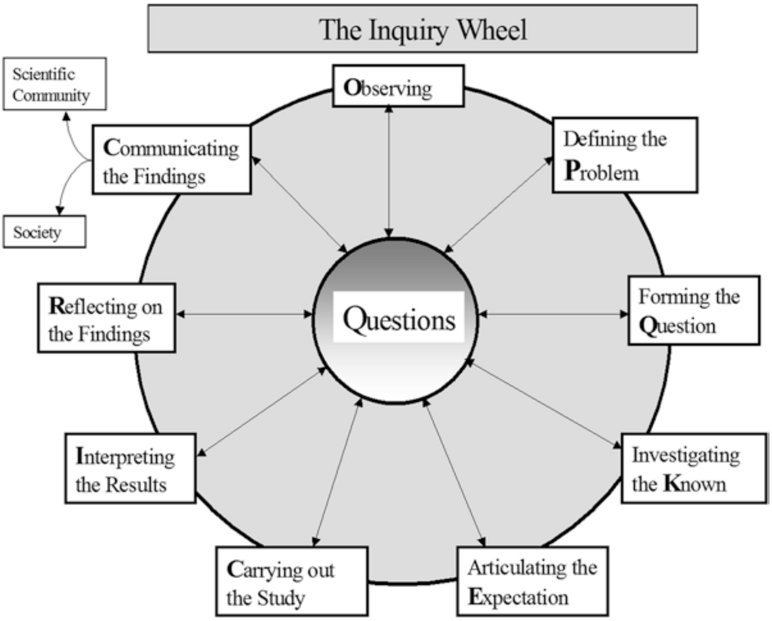

Fig. 6.1 The inquiry wheel: a model to show diverse pathways in science

the collection of scientists' responses. Each stage of the inquiry wheel is based on scientists mentioning important components of scientific inquiries. Though no science faculty member mentioned every stage and the frequency of use of each stage mentioned varied, each stage enhances the overall larger conception of interviewed scientists' conceptions of scientific inquiry (Reiff 2004).

The viewpoint of inquiry shown by the wheel contrasts sharply with the static and linear presentation of the scientific method found in modern science textbooks. The inquiry wheel is a dynamic representation of scientific processes, which continues as long as questions both large and small continue to fuel the investigation. Unlike the stepwise method, this model clearly shows the reality of many pathways to answering a question. Scientists—even the same scientist—may not follow the exact path for every investigation. Scientists "must understand science as a continuing process of inquiry, not as a set of firm answers to particular questions" (NSSE 1960, p. 31). The stages interviewed scientists shared and the descriptions of these processes were used to construct the inquiry wheel.

In this investigation of scientists' conceptions of scientific inquiry, Reiff (2004) found scientists most commonly mentioned "questions" (83%) as an essential stage of an inquiry investigation.

A geographer from this research described the central role of questions as:

> You should question everything. Question, question, question. Why, why, why? If nothing else, science is important for that. It keeps everybody on their toes. If there were more scientists, we would be on our toes. We are not on our toes.

Another frequently cited element in the inquiry process is the importance of "reflection" (61.3%). This finding corresponds to the significance of reflection mentioned by Roberts 1989; Beveridge 1957; Einstein 1944; Zinsser 1940, but does not correlate to discussions of inquiry in science textbooks. Out of 40 science textbooks surveyed, only two included reflection as part of an inquiry investigation in either text or in figures of the scientific method (Reiff 2003).

The inquiry wheel expands on the traditionally defined steps of the traditional scientific method by including stages in an investigation not commonly depicted in science textbooks. The wheel should not be seen as a cycle with one stage leading directly into another stage but is an iterative process where the investigation can begin at any stage and stages can be repeated depending on outcomes in the investigation. This fluid approach is indicated by double-headed arrows on the figure and better portrays how science is actually practiced in contrast to the standard "checklist" often found in textbooks. In the inquiry wheel model, scientists generate questions along each stage and revisit previous stages whenever needed. These questions and their answers are the force necessary to turn the wheel for an investigation to proceed.

Some research scientists interviewed (Reiff 2004) had strong opinions about how the scientific method is portrayed not only in textbooks but also in the classroom. One biologist critiqued the scientific method by saying: "The thing that happens in high school is they try to force everyone to turn their science project into the scientific method with a hypothesis and a prediction. It's absolute gibberish. It doesn't work that way." Other scientists described the process of repeating stages as an important part of the process of scientific inquiry. An anthropologist explains the nonlinearity of scientific inquiry:

> Now will they always follow along a scientific protocol or step-by-step methodology? I don't think so but then science doesn't either. Hypothesis, methodology, testing results, conclusion. Things don't move around in quite that progression; things get bumped around a bit and, I think, in everyday life I think it's the same way. You run into problems and questions and then can use science.

Consistent with scientists' descriptions of their scientific endeavors in the literature, science does not proceed in a step-by-step format with each step checked off before proceeding to the next step (Conant 1947). Science is often presented as a product (Lederman 2003) not as a process of discovery, of failures, or of persistence. Biologist, Judith Ramalay, describes the scientific process:

> People who think science is a product rather than a messy process of inquiry can become profoundly uncomfortable when they are brought face to face with the uncertainties and arguments at the frontiers of science (2003, p. 228).

The inquiry wheel does not restrict investigations to a single method using the experimental approach; the use of the phrase *carrying out the study* broadly includes multiple pathways and approaches to scientific inquiries. Science textbooks and typical science competitions commonly present the experimental approach as the only one version of scientific methodology (Cooper 2002; Lederman 1998; Gibbs and Lawson 1992; Brush 1974). In reality, scientists use a plurality of approaches that include descriptive, exploratory, correlational, experimental, or some combination of methods (Cooper 2002; Sterner 1998; Bybee 1997; Bauer 1992; Keller 1983; Goodfield 1981; Holton 1964; Glass 1967; Beveridge 1957; Conant 1947). Other stages on the inquiry wheel such as observing, communicating, reflecting, and interpreting are represented equally with carrying out the study to denote the significance of scientists spending an equal or greater amount of time on these other stages of an investigation.

The inquiry wheel provides the flexibility in that it shows scientists can begin an investigation anywhere along the overall continuum. In fact, the scientists interviewed mentioned many of these shared stages with varying starting points for investigations (Reiff 2004). Most geologists described observation as the first step in an investigation but for others, questions were the instigator of investigations. Communication occurs throughout a study in both formal and informal ways. The inquiry wheel shows the dynamic nature of scientists beginning at various stages, repeating steps, and generating questions during an investigation.

6.3 Teaching Authentic Scientific Inquiry

"Understanding [authentic] scientific inquiry can change patterns of teaching behaviors and activities in ways that are more significant and enduring than merely supplying teachers with new activities" (Bybee 1997, p. 203). As has been pointed out, too often in science classrooms, students skip the process of an investigation and are primarily concerned with the product. When students are given opportunities to engage in the process of science they do so guided by a step-by-step method that is little more than a shadow of authentic inquiry. Therefore, real science involves students understanding that not all investigations are experimentally driven nor are they mediated by a standard set of steps. The traditional scientific method list of steps should be placed within the larger context of scientific discoveries, creative approaches, and unexplored questions. This section will discuss the use of the inquiry wheel in instruction and will provide brief sketches of ways that may guide scientific inquiry.

6.3.1 The Inquiry Wheel

The Inquiry Wheel is a more accurate description of scientific inquiry generated from interviews with working research scientists and can be used as a framework to help students see science authentically as both nonlinear and multidimensional (Reiff 2004). At the lower grades, students can begin with basic components of an inquiry investigation—asking questions, making observations, and communicating with peers—and then expand on skills such as making connections in the data, selecting tools, techniques, and methods, investigating known information, and reflecting on the findings in upper grades. Instruction should move beyond the basic level of making observations and classifying.

The inquiry wheel can also be used to enhance understandings of the nature of science (NOS) by portraying a more accurate depiction of science as a dynamic and highly evolving endeavor. With questions at the center and chances to move freely about the wheel, students take an active role in participating in science learning. The static, linear depiction of the traditional scientific method does not reflect the role of questions in shifting the scientific knowledge base. Science educators can compare conceptions of the NOS before and after the use of this new model in inquiry investigations. Do students who use the inquiry wheel have improved understandings of the NOS than those using the traditional scientific method? Science educators can determine if the combined use of explicit instruction (reflection and discussions) with more implicit instruction (the inquiry wheel) can improve understandings of the NOS.

The following paths for *carrying out the study* in the inquiry wheel portray the diverse ways science advances through serendipitous moments, thought experiments, and varying research strategies (descriptive, exploratory, correlational, experimental, or a combination). The applicability of utilizing multiple approaches to carrying out scientific investigations further explicates the nature of science (NOS).

6.3.2 The Role of Serendipity in Science

Though scientists can and do plan the framework for investigations, they also value unplanned connections occurring through serendipitous moments (Roberts 1989). New theories can be conceived from a flash of inspiration, an accidental observation, a functional need, strange coincidences, or even clumsiness. Most scientists do not consider that serendipitous moments diminish the merit of discoveries (Keller 1983). The role played by chance in discovery is seldom recognized, understood, or appreciated as pointed out by Beveridge 1957, p. 32 who states, "Books written on the scientific method have omitted the reference to chance in discovery." Serendipitous moments do not happen unless the observer is receptive to thinking in different ways and places. The scientist who possesses thorough knowledge of the subject matter and who does not dismiss conflicting, seemingly trivial, and annoying results will be more likely to experience these unexpected moments. Louis Pasteur perceptively explains this readiness with his famous quip, "Chance favors the prepared mind" (quoted in Roberts 1989, p. 244).

Beveridge (1957) defines these serendipitous moments as "a sudden enlightenment or comprehension of a situation, a clarifying idea which springs into the consciousness, often, though not necessarily, when one is not consciously thinking of that subject" (p. 68). Messages from the subconscious cannot be retrieved if the mind is occupied with thoughts, worries, or is fatigued. The more passionate a scientist is about a problem the more likely ideas will break through to the conscious.

This process usually occurs after much deliberation—conscious and unconscious. Famous ideas have come to scientists (Einstein, Descartes, Wallace, and Cannon) while they were sick in bed, lying in bed, or just awakening when the consciousness is released of external obligations. Engineer James Brindley would go to bed for several days when faced with a difficult problem. German chemist Kekule pondered the conceptualization of the benzene ring while napping:

> I turned the chair to the fireplace and sank into a half sleep. The atoms flitted before my eyes. Long rows, variously, more closely, united; all in movement wriggling and turning like snakes. One of the snakes seized its own tail and the image…. As though from a flash of lightning I awoke; I occupied the rest of the night in working out the consequences of the hypothesis (quoted in Beveridge 1957, p. 56).

Perhaps what can be learned here is that chance also favors the *relaxed* mind.

A frequently given example of a serendipitous moment occurred with bacteriologist Alexander Fleming. He was engrossed in examining different bacterial cultures when a spore landed in his uncovered Petri dish. Instead of disposing of the "contaminated" Petri dishes, Fleming recognized the unusual clearing around one of the bacterial cultures as indicative of suppressed bacterial growth. Fleming was amazed that out of thousands of molds, the mold penicillin inhibited bacterial growth (Roberts 1989).

Another example of a serendipitous moment resulting in a discovery is the story of Archimedes. Summoned by the king to determine if the majesty's crown was made of pure gold or of an alloy, Archimedes was presented with this problem to solve. A great mathematician of third century B.C., Archimedes determined, in order to solve this problem, the volume of the crown must be known—a feat considering the object's irregularity. While bathing in the public baths of Syracuse, he noticed the volume of the overflow of water was exactly equal to the part of his body placed in the tub. At this moment, Archimedes jumped up naked from his tub and ran through the streets screaming, "Eureka! Eureka!" Knowing the mass and now the volume of the crown, Archimedes could determine the density of the crown and compare this figure to the density of gold (it turned out the crown was not made of gold).

Serendipitous moments can also happen as a result of clumsiness: Charles Goodyear accidentally heated rubber with sulfur; the chemist, Fahlberg, spilled saccharin on his hand and tasted it; the worker who spilled a newly developed product (known later as Scotch guard) on a tennis shoe noticed its repellence to stains. Other moments can occur because of functional purposes. In 1974, Art Fry set out to make bookmarks and started considering other useful ideas with pieces of paper. He then stumbled across the idea of Post-it Notes (Roberts 1989). Other serendipitous moments include the development of the smallpox vaccine, the identification and isolation of insulin, the discovery of Pluto's moon, Teflon, Velcro, X-rays, and many other phenomena. Albert Szent-Gyorgyi eloquently states, "Discovery consists of seeing what everybody else has seen and thinking what nobody has thought" (quoted in Roberts, p. 245).

6.3.3 The Role of Thought Experiments in Inquiry

Another way to conjure new ideas or theories is through "thought experiments." Time allotted for thinking is crucial for seeing patterns, making decisions, and improving scientific studies (Goodfield 1981). In this case, concepts are clarified and discoveries are made through rigorous thinking (Brown 2001). John Dewey calls mulling over ideas "reflective thinking" (1933). The main distinction between a trained and an untrained thinker is the ability to sift out irrelevant evidence. Beveridge (1957) describes the most effective investigators as those who conceptualize problems beforehand and design experiments to address these questions. Original ideas are more likely to arise with a depth of knowledge in the field and a breadth of knowledge in others. Scientists who have made significant contributions usually have wide interests in other fields, for example, Einstein.

"All creative thinkers are day dreamers" (Harding, quoted in Beveridge 1957, p. 55). Clerk Maxwell made mental pictures of every problem to stimulate the imagination (Beveridge 1957). Einstein also spent considerable time conceptualizing aspects of his theory of relativity through thought experiments, as indicated by his statement "From the beginning it appeared intuitively clear to me that, judged from the standpoint of such an observer, everything would have to happen according to the same laws as for the observer, who relative to the earth, was at rest" (Einstein 1944, p. 53).

Depending on the science discipline, the scientist's previous experience along with the type of questions asked can widely impact the methodological choices made when individual scientists conceptualize and embark on scientific investigations. Scientific disciplines also have different modes of inquiry. Physics, an older science, tends to be more theory-oriented whereas geology, a newer science, is heavily based on description. Scientific language within each discipline is also theory-laden; academic training and the reigning paradigms of the time shape scientists in their respective disciplines (Kuhn 1962).

6.3.4 Observation and Description as Scientific Method: The Role of Qualitative Research

In a well-developed science such as the physical sciences, abstraction is more common than in a newer science where description is the primary method of obtaining evidence (Knight 1986). The experimental method (the scientific method) is not appropriate in other forms of research such as descriptive biology, evolutionary biology, or observational ecology. In these studies, the scientist has limited control over extraneous variables. Examples of descriptive methodology include clinical observations, case studies, surveys, questionnaires, interviews, natural observation (with and without intervention), and archival studies (Sterner 1998). In medicine, descriptive analysis can be used to record symptoms of depression during antenatal and postpartum phases of pregnancy. An experiment is not conducted but rather clinicians gather responses from pregnant women in order to look for patterns in the data and to explain phenomenon (White and Frederiksen 1998). Jane Goodall (1967) was a pioneer in studying the behavior of chimpanzees. Because little was known about group behavior, foraging techniques, or caring for their young, Dr. Goodall used nonintervention methods and descriptive studies to record observations of chimpanzees in field notes. Within her field notes is a detailed description of chimpanzees' (*Pan troglodytes*) reaction to snakes that could never have been anticipated or would not have been discovered through experimentation.

In reality, scientists conjure several alternate hypotheses to explain phenomenon, a process called "brainstorming" (Gibbs and Lawson 1992, p. 146). Hypotheses are not entirely derived from observation but from past experiences (Gibbs and Lawson 1992; Kuhn 1962). Animal behavior expert Tim Caro investigated gazelles' slotting behavior (the tendency to leap into the air) in Kenya's Serengeti Plain (1986). Caro conceptualized multiple hypotheses on slotting and gazelles based on his past experiences with predator-prey relationships. His hypotheses included the possibility that gazelles slot to (1) warn other gazelles about the danger, (2) draw attention away from the vulnerable offspring, and (3) let the predator know it has been seen. Questions can generate different lines of inquiry such as an *exploratory study* where the scientist observes the behavior of gazelles and records detailed notes in a field notebook. In a *correlation study*, the scientist after observing gazelles slotting records possible factors affecting the gazelles' behavior. Finally in an *experimental study* the scientist narrows down possible causes for the behavior and conducts a study to determine the most robust explanation based on the evidence.

6.3.5 Experimentation in Inquiry

In correlational studies, scientists try to determine if a relationship exists among the variables, not if one causes the other (Sterner 1998). Relationships can be graphed on scatterplots to indicate positive or negative correlations (Fraenkel and Wallen 2000). Correlational studies also serve as predictors for determining the likelihood of a variable affecting another. Once a relationship is established, experimental methods can *then* be used to determine causality.

The most frequently portrayed process of science is the experimental method. This research practice determines cause and effect relationships through organizing a controlled experiment with the goal of manipulating one variable at a time and measuring the outcome. Experimental research is the most commonly portrayed version of science in textbooks but this limited portrayal omits the diverse pathways to scientific progress as previously discussed (Bauer 1992; Gibbs and Lawson 1992; Brush 1976; Medawar 1963).

Modifications to lesson plans can help diversify scientific inquiries and illustrate the multiplicity of scientific processes through the following instructional strategies: the inquiry wheel, narratives, re-enactments, out of class problem solving, discussions, debates, analyzing quotes, and revamping assessments. These adjustments can supplement a science textbook to expand and revive science to a lively process characterized by controversy, nonlinear pathways, diverse research methods, unplanned realizations, reflection, persistence, imagination, open-mindedness, and creativity. Science is portrayed as lifeless in textbooks because inquiry is omitted as a vital function. Without inquiry science would remain in a state of inertia.

6.4 Conclusions

Helping students understand that there are many diverse pathways scientists use to reveal knowledge about the natural world ensures learners see these as part of their classroom experiences. Doing so will increase the likelihood students will develop a conception of science more aligned with actual scientific practices. Instead of showing experimental methods as the sole or even primary means to scientific advancements students should experience a broad range of the paths scientists take or have taken as part of authentic scientific inquiry (Anderson 2002; NRC 1996, 2000; White and Frederiksen 1998; Bybee 1997; AAAS 1990, 1993; Klopfer 1969; Hurd 1969). Only through an authentic inquiry experience will we foster learners who can pose questions, seek evidence for and against claims, understand how to evaluate evidence, and understand science as a variety of processes by which the world can be understood. Students should not only be exposed to the fundamentals of a discipline but also to the attitudes of approaching and addressing inquiries necessary for scientific progress (Bruner 1960).

Simply exposing students to the “traditional” step-by-step scientific method is an incomplete representation of the range of applicable scientific processes that comprise inquiry. Unfortunately, the public view of scientific processes is faulty due in large measure to the misrepresentations of science textbooks. Scientists have clearly made the distinction between what they actually do and what is shown in textbooks, but science education has not explicitly incorporated diverse scientific pathways (thought experiments, correlational, descriptive, exploratory studies, and serendipitous moments) as part of a curriculum valuing what scientists do and how they think.

The linear, step-by-step image of the scientific method has become so ingrained in our culture that we need a commitment from curriculum developers, science educators, and teachers to dispel the myth of a single scientific method through diversifying scientific inquiries in textbooks and in science instruction. The result of scientific journeys is not to arrive at a stopping point or the final destination but to refuel with questions to drive the pursuit of knowledge. The use of the “inquiry wheel” and its sharp contrast with the static and linear presentation of method along with discussions and classroom experiences in various ways of inquiry knowing can be the force to reach this goal of science authenticity.

References

American Association for the Advancement of Science. (1990). *Science for all Americans*. New York: Oxford University Press.

American Association for the Advancement of Science. (1993). *Science for all Americans*. New York: Oxford University Press.

Anderson, R. D. (2002). Reforming science teaching: What research says about science teaching. *Journal of Science Teacher Education, 13*, 1–12.

Bauer, H. H. (1992). *Scientific literacy and the myth of the scientific method*. Chicago: University of Illinois Press.

Beveridge, W. I. B. (1957). *The art of scientific investigation*. New York: W.W. Norton & Company Inc.

Bridgman, P. W. (1955). *Reflections of a physicist*. New York: Philosophical Library Inc.

Brown, R. J. (2001). *Who rules in science?* Cambridge, MA: Harvard University Press.

Bruner, J. (1960). *The process of education*. Cambridge, MA: Harvard University Press.

Brush, S. (1974). 'Should the history of science be rated x'? *Science, 183*, 1164–1172.

Brush, S. (1976). 'Can science come out of the laboratory now'? *Bulletin of Atomic Scientists, 32*, 40–43.

Bybee, R. W. (1997). *Achieving scientific literacy: From purposes to practices*. Portsmouth: Heinemann.

Caro, T. M. (1986). The function of slotting: A review of the hypotheses. *Animal Behaviour, 34*, 649–662.

Conant, J. B. (1947). *On understanding science*. New Haven: Yale University Press.

Cooper, R. A. (2002). Scientific knowledge of the past is possible: Confronting myths about evolution & scientific methods. *The American Biology Teacher, 64*, 427–432.

Dewey, J. (1933). *How we think*. Boston: Heath & Co.

Dressel, P., Burmester, M. A., Mason, J. M., & Nelson, C. H. (1960). How the individual learns science. In N. B. Henry (Ed.), *Rethinking science education: The 59th yearbook for the study of education* (pp. 39–62). Chicago: University of Chicago Press.

Duschl, R. A. (1985). Science education and philosophy of science; twenty-five years of mutually exclusive development. *School Science and Mathematics, 15*, 36–43.

Duschl, R. A. (1990). *Restructuring science education: The importance of theories and their development*. New York: Teachers College Press.

Einstein, A. (1944). Russell's theory of knowledge. In P. A. Schilpp (Ed.), *The philosophy of Bertrand Russell*. New York: Harper and Row.

Feyerabend, P. (1975). *Against method*. London: New Left Books.

Fraenkel, J. R., & Wallen, N. E. (2000). *How to design & evaluate research in education* (4th ed.). Boston: McGraw Hill.

Gibbs, A., & Lawson, A. E. (1992). The nature of scientific thinking as reflected by the work of biologists & biology textbooks. *The American Biology Teacher, 54*, 137–152.

Glass, B. (1967). The most critical aspect of science teaching. *The Science Teacher*, 19–23.

Goodall, J. (1967). *My friends the chimpanzees*. Washington, DC: National Geographic Society.

Goodfield, J. (1981). *An imagined world. A story of scientific discovery*. New York: Penguin Books.

Hawkins, D. (1965). Messing about in science. *Science and Children, 2*(6), 5–9.

Holton, G. (1964). Modern science and the intellectual tradition. In A. B. Arons & A. M. Bork (Eds.), *Science & Ideas* (pp. 175–190). Englewood Cliff: Prentice-Hall, Inc.

Holton, G. (1988). *Thematic origins of scientific thought: Kepler to Einstein* (Rev. ed.). Cambridge, MA: Harvard University Press.

Hurd, P. D. (1969). *New directions in teaching secondary school science*. Chicago: Rand McNally.

Keller, E. F. (1983). *A feeling for the organism: The life and work of Barbara McClintock*. New York: W.H. Freeman and Company.

Klopfer, L. E. (1969). The teaching of science and the history of science. *Journal of Research in Science Teaching, 6*, 87–95.

Knight, D. (1986). *The age of science: The scientific world-view in the nineteenth century*. New York: Basil Blackwell Inc.

Kuhn, T. (1962). *The structure of scientific revolutions*. Chicago: University of Chicago Press.

Lederman, N. G. (1998). The state of science education: Subject matter without context. *Electronic Journal of Science Education, 3*, 1–11.

Lederman, L. M. (2003). Obstacles on the road to universal science literacy. In *Science literacy for the twenty-first century*. Prometheus Books: New York.

McComas, W. F. (1996). Ten myths of science: Reexamining what we think we know about the nature of science. *School Science and Mathematics, 96*, 15–21.

Medawar, P. B. (1963). Is the scientific method paper a fraud'? *The Listener*, 377–378.

National Research Council. (1996). *National science education standards*. Washington, DC: National Academy Press.

National Research Council. (2000). *Inquiry and the national science education standards*. Washington, DC: National Academy Press.

National Society for the Study of Education. (1960). *Rethinking science education: The 59th yearbook for the study of education*. Chicago: University of Chicago Press.

Ramaley, J. (2003). Building a public understanding of science: A matter of trust. In *Science literacy for the twenty-first century*. Prometheus Books: New York.

Reiff, R. (2003, January). *The portrayal of the scientific method in science textbooks: Should the myth continue?* Paper presented at the meeting of the Association for the Education of Teachers in Science. St. Louis, MO.

Reiff, R. (2004). *Scientists' conceptions of scientific inquiry: Revealing a private side of science*. Doctoral dissertation. Retrieved from ProQuest Dissertations and Theses database. UMI No. 3134038.

Reiff, R., Harwood, B., & Phillipson, T. (2002, January). *The inquiry wheel: A research model for doing scientific inquiry.* Paper presented at the meeting of the Association for the Education of Teachers in Science. Charlotte, NC.

Roberts, R. M. (1989). *Serendipity: Accidental discoveries in science*. New York: Wiley.

Schwab, J. (1962). The teaching of science as enquiry. In *Teaching of science* (pp. 1–103). Cambridge, MA: Harvard University Press.

Sterner, R. T. (1998). The scientific method: An instructor's flow chart. *The American Biology Teacher, 60*, 374–378.

White, B. Y., & Frederiksen, J. R. (1998). Inquiry, modeling, and metacognition: Making science assessable to all students. *Cognition and Instruction, 16*, 3–118.

Ziman, J. (1984). *An introduction to science studies: The philosophical and social aspects of science and technology*. Cambridge, MA: Cambridge University Press.

Zinsser, H. (1940). *As I remember him*. Boston: Brown and Co.

Chapter 7
Exploring the Challenges and Opportunities of Theory-Laden Observation and Subjectivity: A Key NOS Notion

William F. McComas

7.1 Introduction

A major aspect of the nature of science (NOS) that should be communicated to students is the idea that scientists—and everyone else for that matter—have prior notions about what they will ultimately "see" when looking at phenomena, and that these prior ideas interact with the act of observation itself. This is not surprising; considering the range of sense data that flow in daily, it is quite useful for the mind to turn itself off—in a sense—when the data are not deemed useful. All of us engage in this form of unconscious selective observation. The situation is the same in classrooms. We tell students when looking through the microscope to "draw what you see," and then question when they have included so many air bubbles. Students learn quickly that these bubbles are not considered useful data and soon fail to include them in their drawings. We often talk about learning to observe as a vital part of school science laboratory work, but how many of us teach students about the limits of observation and the potentially confounding role of prior knowledge when making observations? These are extraordinarily important lessons that relate closely to the nature of science itself and the notion that observation-making is very tricky business.

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_7

7.2 Observations, "Theories," and the Myth of Complete Subjectivity

Norris (1985) correctly stated that observation is fundamental in science but warns that it is a misconception to suggest that observation is "the simplest of all intellectual activities of scientists" (p. 817). To the contrary, the act of observing is far from something that is uncomplicated, automatic, or even trivial as some might believe. All observations are directed by advance notions of what is likely to be observed, although the observer typically does not appreciate the role played by this advance expectation. Observation, therefore, is an active rather than passive process (Hainsworth 1956) comprising at least three steps: a source [the observed object or phenomenon] that releases information, the transmission of data, and the reception of these data by the observer or instrument (Shapere 1982). This last point has become known as "theory-ladenness" "the view that observation cannot function in an unbiased way in the testing of theories because observational judgments are affected by the theoretical beliefs of the observer" (Franklin 2015, p. 155).

The transmission of useful data from object through observer may seem linear, but we would be wise to heed the warning of Alphonse Bertillon (1853–1914), one of the founders of forensic science, who said, "one can only see what one observes, and one observes only things that are already in the mind." What this means to scientists, science teachers, and science students is that prior knowledge both helps to direct and confound the act of observing. Although this is a vital element of the nature of scientific investigation, the pitfalls and potential of observation are rarely communicated to those engaged in the science learning enterprise. "Observations … mark the beginning points of reasoning in the area of knowledge in question, the basis upon which other knowledge rests" (Norris 1985, p. 824); observation is more complex than the simple act of looking at or measuring something. Rather, observation depends on inferential procedures (Duschl 1985; Norris 1985).

The prior inferences or conceptions held by observers are what Hanson (1958) called "theory-laden" and are formed by the intermingling of knowledge, background, and observation. Hanson (1958) states further that the "observation of χ is shaped by prior knowledge of χ" (p. 19). Gould (1994) discusses the issue of the complexity of observation and theory development by saying, "[S]cientists … tend to be unaware of their own mental impositions upon the world's messy and ambiguous factuality. Such mental impositions arise from a variety of sources, including psychological predisposition and social context" (p. 67). "When scientists adopt the myth that theories arise solely from observations, and do not grasp the personal and social influences acting on their thinking, they not only miss the causes of their changed opinions; they may even fail to comprehend the deep mental shift encoded by the new theory" (p. 68).

Before proceeding further, it would be wise to consider the different uses of the word "theory," found in the expressions "theory-laden" or "theory-based" observation and in the quotes from Gould. Hanson is using "theory" in the commonsense fashion where the term means an idea. So here we see that ones' prior ideas can dramatically alter the nature of the observations they make. Gould does not help much when he seems to refer to any scientific idea as a "theory," but he is correct that scientists and other observers often pay little attention to "the personal and social influences" (p. 67) that act upon thinking, but the results of the experiment presented later in this chapter clearly demonstrate that they should.

So, we can see that the label of "theory-laden" observation is problematic because of the potential for confusion that exists when considering the more precise definition of "theory" as ideas that explain why and how laws operate as they do. It would be far better to talk about *idea-based observations* or *prior concept-based observations*, but it would be foolish to expect that the "theory-laden" or "theory-based" label will be easily replaced. The literature is replete with references to this issue (Brewer and Lambert 2001) so we will maintain it here, but with quotes.

There has been continued interest among historians and philosophers of science on the issue of "theory." Brewer (2015) and Franklin (2015) have discussed the role of "theory" in the conduct of experiment and Schindler (2013) offered three related ideas about what theory-ladenness means in practice. He states that (1) observations are linked to some guiding idea or "theory," (2) that these guiding ideas help to make some observations more important or worthy than others, and (3) that our theories impact what we "see." In a comprehensive article replete with example, *Learning to See*, that strongly supports many of the themes expressed here the author tells us that "learning to see I not an innate gift; it is an iterative process, always in flux and constituted by the culture in which we find ourselves and the tools we have to hand" (Tracy 2018, p. 242).

Finally, this notion of "theory-based" observation provides an opportunity to discuss two related notions, that of "confirmation bias" and the closely related NOS notion, that of subjectivity in science. First a brief mention of the idea of confirmation bias which is the tendency to interpret new evidence as confirmation of ones' existing ideas or beliefs (Nickerson 1998). One side of the confirmation coin is almost inevitable. We somewhat naturally and even unconsciously pay more attention to information sources that are likely to speak to our deeply held views because we are more likely to value and respect such sources of information. The other perspective is that we actively look for and attend to information sources only that support and reinforce our world views probably to avoid being challenged. Even if we can forgive ourselves these natural inclinations, those who truly want to understand a phenomenon must work assiduously against only confirming what we think we already know. One proviso is that any source of information whether confirming or not must provide valid and reliable data and in the era of "fake news" in which this chapter was written, making that determination can be problematic.

The issue of subjectivity as a key NOS notion is discussed in some detail in Chap. 2 of this book, but a review here will be useful to link it with the challenges of observations. As we have established, scientists have their own advance notions about the potential meaning of any observation. Therefore, it is useful for students to understand that science itself possesses a more subjective character than they might have thought. This is certainly true when considering individual scientists and perhaps even laboratory working groups. As we will see in the sections that follow while there are some advantages to holding a prior view about the nature of evidence and the expectations of observations this can cause problems.

In the final analysis even though there is a subjective character to science, the scientific enterprise is populated by diverse people with a variety of views who operate within a collective check and balance system. So, while it is quite reasonable and accurate to admit that science has subjective elements—particularly as new observations and conclusions are initially being offered—the final judgment of science becomes increasingly objective as conclusions are vetted by and through the greater scientific establishment tempered by time and the further considerations of scientists in the future. The phrase the "truth will out" widely quoted from Shakespere's *Merchant of Venice* neatly summarizes and predicts the work of the scientific enterprise in addressing the challenges of scientific subjectivity.

7.3 Pros and Cons of "Theory-Based" Observations in Science

So, let us return to the issue that all of us—scientists included—make observations and interpret what we see based on our prior understanding and experiences. This reality "To the observing scientist, [theory] is both friend and enemy" (Boring 1950, p. 601). From a positive perspective, knowing what to look for and ignoring what is likely to be useless or distracting is useful. Beveridge (1957) was correct when he pointed out that "the prepared mind may make many more significant observations than the unprepared" (p. 46). Darwin (1850) who, when asked about his method of observation, stated that he speculated on any subject he encountered. He stated, "I can have no doubt that speculative men [sic], with a curb on, make far the best observers…" Mayr (1991) reflected on this by stating that speculating or theorizing (another dubious use of the term) is a "time-honored method of the best naturalists. They observe numerous phenomena and always try to understand the how and why of their observations. When something does not fall into place, they make a conjecture and test it by additional observation…" (pp. 9–10). Here it would seem that knowing what to look for, knowing in advance what is useful information, and then speculating on what it means is how the best scientists must all work.

As an example, consider the work of physicist Robert Millikan. He designed his famous oil drop experiments, to determine the charge on the electron. After his death, Millikan's laboratory notebooks—never intended to be published—became available for study (Franklin 1981). These laboratory journals contained Millikan's notations regarding which findings he thought were publishable and which were too far away from his expected value. His notebooks reveal that Millikan frequently found reasons to discard data when those values fell outside the anticipated range, but he did not examine the result as closely when the data conformed to his expected value. One could say that he knew what to look for and did so with passion.

On the other hand, it is easy to imagine that when an observer is so sure of the data that will be observed, in which direction they should be looking, and what the data imply, it would be very easy to miss something of interest. The history of science is full of examples of older scientists—presumably with more prior ideas—overlooking interesting findings because they simply do not correspond with their world view and expectations. One particularly fruitful example of this would be the long ranging debate about the cause of the demise of the dinosaurs at the end of the Cretaceous period. While all scientists agreed that dinosaurs met their end about 66 million years ago, many who preferred other explanations had trouble seeing that multiple lines of evidence pointed to an extraterrestrial impact. It was simply not part of their prior expectation that a huge object from space might have smacked the Earth, created cataclysmic fires generating massive amount of soot that in turn blocked sunlight for decades, and generally wrought havoc on food chains worldwide. Likewise, a previous generation of earth scientists could not imagine that the continents, in fact, did change position even when faced with the strong suggestion that South America and Africa really did embrace each other at some point in the past.

7.4 Considering the Challenges of Observations in Science Instruction

Certainly, the issue of making observations is a topic of considerable interest both in understanding how science is conducted and in appreciating the strengths and limitations of scientific methodology. So, it is no surprise that for much of the past century, science educators have advocated specific training in observational skills. Johnson (1942), for instance, reports that his department designed a program “to train students in observation and accurate recording” (p. 57). Norris (1984, 1985) provided an overview of the philosophical basis of observation and a definition of observational competence but this view was criticized by Willson (1987) who stated that “Norris failed to differentiate between two kinds of observation, theory-building and theory-confirming observation” (p. 283). Willson believed that science educators have neglected to distinguish the nature of observations made by expert scientists from those made by novice students. Even this distinction, while assisting science educators to see observation as a high-level process, omits mention of the role of expectancy in coloring the way in which observations are made both by students and by scientists.

One of the so-called “alphabet soup” curriculum projects in the United States, *Science: A Process Approach* (SAPA 1967), was designed to acquaint students with how science is done by suggesting that if students would understand and practice the skills of scientists both prior goals would be accomplished. To that end, the designers of S-ASA identified 13 skills—called process skills—seen as common investigative tools found across all science disciplines. Among these skills, observation was considered one of the most basic, an unfortunate assumption.

In their text on science teaching methods, Collette and Chiapetta (1994) made a rare reference to the challenges of observation in the education of future science teachers. They pointed out that what people observe depends upon their interests and that "false observations can occur when the senses provide the wrong information … [and that] the mind plays tricks on the observer…" (p. 38). They close their short section on observation by stating that "[a]though observation seems to be the most basic and fundamental of the inquiry skills, it is a complex activity that merits careful study in and of itself" (p. 38). Even as science educators pay more attention to the problems of observation, few have provided suggestions for what teachers or science methods instructors can do to examine observation in the classroom, to instruct students about the range of issues that impact observation, or to avoid the problems associated with this important process skill.

While few would argue that observation is an important science process skill, given what we know about observation, only those who are naive would characterize observation as basic. As mentioned, all observers have their own ideas about the way nature operates and this prior knowledge plays a role in the way in which students make observations. Teachers may defend the laboratory experience by stating that hands-on work gives students the opportunity to observe scientific phenomena for themselves, but observation of phenomena and interpretation of data are not simple tasks. There is no suggestion that schools should scale back the use of laboratory activities but rather we should help students understand that observation is not as straightforward as they perhaps believe. In doing this, we would be teaching students a valuable NOS lesson related to the *Human Dimension of Science*. In this concluding section, we will explore a real-world illustration of the impact of prior knowledge on observation by exploring a phenomenon known as the expectancy effect. As you will see, this is both a challenge and an opportunity.

7.5 Prior Knowledge and the Expectancy Effect in School Science

Expectancy is a label for an issue within what is called experimenter, observer, or investigator effect in the psychological literature and may be thought of as the outcome associated with the inevitable presence of prior knowledge on the part of an observer. Expectancy occurs when investigators, with no desire to misrepresent results, equate "what they think they see, and sometimes what they want to see, with what actually happens" (Lane 1960, p. 85).

According to Rosenthal (1976), the author of the most comprehensive treatise on this topic, there are two main classes of experimenter effects—biosocial and non-biosocial. In the biosocial realm, a subject of study may behave differently because of some characteristic of an observer. This result is primarily found in behavioral studies with humans but has been noted for other species including dogs and horses. Rosenthal reports that canines have been found to have differential heart rates when a scientist is visible to the animal. Investigator variables shown to interfere with expected results in human behavioral studies include the scientists' age, religion, gender, the degree of hostility, dominance or warmth, the level of acquaintanceship with the subject, and anxiety.

The category of experimenter effects of most interest to science educators are the nonbiosocial ones since these operate in all investigative settings not just in those that involve experiments with people and higher animals. Nonbiosocial experimenter effects include the interpreter effect, the effect of early data returns, and expectancy. The interpreter effect occurs when two or more individuals observe the same phenomenon but evaluate the results differently depending on their prior knowledge. Interpreter effects drive the expectation of the experimenter and influence what is observed, what is ignored as irrelevant, and what data are called into question, and ultimately what is published (Sheldrake 1995). The example of Millikan provided earlier might be thought of as an example of this effect.

In the case of early data returns, investigators' expectations about the eventual result are swayed by the nature of the first data gathered, an effect noted as early as 1885 (Rosenthal 1976). Early data returns can influence the investigator either toward or away from a given hypothesis. Returns which agreed with the predicted result strengthen the expectancy effect whereas weak returns may modify the original expectation, but both will tend to influence the observer and tend to be self-fulfilling prophecies. In science classes, it is common for students to collect a few data points and then become satisfied that they know the end results. Or, as Rosenthal (1976) states, "perhaps early data return that disconfirm the experimenter's expectancy leads to a revision of the expectancy in the direction of the disconfirming data obtained, thereby making it more likely that subsequent data will disconfirm the original hypothesis but support the revised hypothesis" (p. 196).

These effects may all play a role in the instructional laboratory, but the experimenter effect of most importance from a NOS perspective is that of expectancy—the idea that observers may "see" what they expect to see. Several studies of this type of biased observation have shown that if an expectation is created in an observer, the observation will be influenced. One interesting example is seen when researchers count the incidence of twisting in the common flatworm *Planaria*. Even among experienced observers, those told that they had "high-twisting" *Planaria* counted more twists than observers told they had "low-twisting" animals. This result occurred even though both "types" of worms were taken from the same batch of animals, all with the same characteristics (Cordaro and Ison 1963). Other experiments with rats labeled as "high-learning" or "low-learning" revealed a similar expectancy effect when these rats were timed running through mazes. Researchers reported that the "high-learning" animals ran the mazes faster than the "low-learning" rats even though all the rats, despite their label, were identical in their maze-running ability (Rosenthal and Fode 1963). Next, we will explore the problem in practice a discussion of data from a classroom experiment and conclude the chapter with the use of the classic old woman/young woman illusion to exemplify the point for students easily.

7.6 The Daphnia Dilemma: An Experimental Illustration of the Challenge of Prior Knowledge

Next, we will discuss a fascinating example of the role played by prior conceptions on students' ability to observe scientific phenomena in the laboratory with a common exercise in which students place stimulants and depressants on *Daphnia*[1] (a common freshwater crustacean) and measure changes in the animals' heart rate. Gray (1996) reported that the exercise did not seem to work as anticipated but stated that it might still be useful in encouraging discussion of the nature of scientific inquiry.

Perhaps the variable most likely explanation of the results was whether the students knew—or thought they knew—what was likely to occur in advance of the actual laboratory trial. This variable, which is called the expectancy effect, is likely known and accepted by members of the science education community, but surprisingly has rarely been a feature of research in science education (Hainsworth 1956, 1958). That is unfortunate given its importance. Observation is discussed and commonly included in science instruction as a common element in laboratory investigations but is only infrequently explicitly examined in school science or tied to the nature of science. A recent exception may be found in Lau and Chan (2013) who investigated ways to teach about "theory-laden" observation by telling some students that vitamin C can be destroyed by heating and telling other students that is cannot be and then having students analyze data with this prior notion in mind.

7.6.1 Methodology

This experiment began by securing a quantity of the freshwater crustacean, *Daphnia magna*, from a biological supply company. The animals were maintained in spring water and fed dried algae as recommended by the supplier for the duration of the investigation. *Daphnia* reproduce readily with a new generation of adults appearing every few weeks. The idea was quite basic; students would be asked to put various solutions (some labeled as stimulant, depressant, or unknown) on the *Daphia* and count the heartbeat to make judgments about the impacts of the

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[1] Daphnia are a common type of freshwater crustacean sometimes called water fleas because of the hopping motion made when they swim. Their transparent shells allow students to see through to the internal organs. The small *D. pulex* has been available for many years, but the much larger *D. magna* has increased in popularity due to the enhanced ease with which students can see key structures.

chemicals introduced. However, in all cases, the various solutions were nothing but pond water and would not be expected to have any physiological effect.

Several classes of biology students were recruited for this investigation. Subjects were all secondary school (ages 14–18) biology students in general biology representing 12 classes at two urban and two suburban schools. All ethnic groups were represented with some skew toward members of minority populations—primarily Hispanic. Males and females were equally represented.

Each pair of students received a set of three dropper bottles containing nothing but the same spring water in which the *Daphnia* lived made by filtering out the animals and debris. This water was put in the containers for each new trial. The use of the same water in which the animals lived made it highly unlikely that it would have any physiological effect when introduced to the animals later. Even though the dropper bottles contained nothing but the spring water in which the animals were reared, one of the bottles was labeled "Stimulant," one was labeled "Depressant," and the final bottle was labeled "Unknown." All dropper bottles and stock culture of *Daphnia* were maintained at the same temperature to ensure that temperature played no role in the experiment. Please note that throughout this paper, the contents of the experimental solutions are indicated in quotations because they consisted of nothing but water in which the animals lived. Students believed them to contain active ingredients.

The students were introduced to the exercise with a diagram of the anatomy of the animal, pointing out the heart and other structures. As an introduction, I discussed the correct technique for counting heartbeats and reviewed what a stimulant and depressant would likely do to the heart rate. Students were told that the stimulant was a weak solution of nicotine, that the depressant was a weak solution of alcohol, and that the unknown could be either nicotine, alcohol, or pond water. Students were assured that they were not being assessed and that the purpose of the exercise was to see if the laboratory activity worked properly. The investigator had a conversation with the students in advance about what was likely to happen to the heart rate of these animals exposed to stimulants and depressants.

The heart rate of *Daphnia* is quite high (approximately 270 beats per minute) and individual students who look at the beating heart while trying to count the beats easily became frustrated and lose count. Therefore, a team approach was devised in which one student would look at the beating heart through the low power microscope objective and gently tap in time with the beating heart. The other student did the actual counting. Pairs of students were given an animal on a depression slide. To keep the animal still, the *Daphnia* were held in place with a few cotton fibers floating in the water. One of the student investigators kept time with a clock that audibly signaled the end of 15 s. During this time, the second student counted and recorded the taps. The resting heart rate of the animal was measured for three 15-second intervals and recorded on a chart provided. Students practiced this counting skill before proceeding with the experimental trials.

Following the practice period, students placed one drop of the liquid labeled "Stimulant" on the animals. After 1 min (presumable to allow the "drug" to take effect), the heart rate was again counted during three trials. The students then placed that animal in a holding container, rinsed and dried the slide, and received a new animal for the second experiment. Again, the resting heart rate for the new animal was determined and the basic procedure was repeated using liquids labeled "Depressant" and, with a third fresh animal, the "Unknown." Students recorded their findings on data sheets provided.

7.6.2 Results

In the first of the three experiments, students reported that the resting heartbeat of the *Daphnia* was approximately 240 beats per minute (bpm) when averaged over three 15-second trials (Table 7.1). Students reported an increase in the heart rate to 276 bpm on average after the introduction of what students thought was a stimulant. ($\Delta = 36$ beats per minute). This increase is significant ($t(138) = -10.9$, $p < 0.001$).

In the next trial, a new animal was used, the "depressant" was introduced, and the heart rate measured. In this case, the average resting heart rate was measured at 256 bpm which students said decreased to 235 bpm ($\Delta = -21$ beats per minute) with the chemical. This decrease is significant ($t(140) = 5.89$, $p < 0.001$).

In the final trial, the same protocol was followed. Another fresh animal was used, the "unknown" was introduced and the heart rate was measured again with a resting heart rate of 252 bpm on average. After introducing the "unknown," students reported that the average heart rate was 260 bpm ($\Delta = 8$ bpm). This change is not statistically significant ($t(125) = -1.6$, $p =$ n.s.) as one would predict if the observers had no reason to expect a given result.

There were a few but quite interesting qualitative results noted when some students made comments while the experiment progressed. At various times in all classes a few students invariably asked why "nothing was happening." This was an indication that students knew what was supposed to occur and were curious that it did not. This was balanced by another group of frequently-heard comments including: "Wow, look how fast the heart is beating!" with the introduction of the "stimulant," or "[the heart] really slowed down," after students put the "depressant" on the animal. Again, there were no active ingredients in any of the dropper bottles so any

Table 7.1 Pair-wise summary statistics and the results of paired *t*-tests for each of the experiment[a]

		Mean (per 15 s)	*N*	Std. Deviation	*t*	df (two-tailed)	Sig.
Pair 1	Resting Set 1	59.85	139	13.59	−10.900	138	$p < .001$
	"Stimulant"	69.07	139	17.61			
Pair 2	Resting Set 2	63.94	141	15.21	5.890	140	$p < .001$
	"Depressant"	58.68	141	15.76			
Pair 3	Resting Set 3	63.09	126	14.15	−1.600	125	n.s.
	"Unknown"	64.90	126	17.55			

[a] Note: the number of pairs of students differs because of missing data and the failure of one class to complete the investigation of the unknown. The resting values are calculated separately because they were for different animals (three per trial) in each experiment

changes to the observed heartbeat were in the students' minds, not in the physiology of the daphnia.

7.7 Discussion and Conclusion

This experiment illustrated the impact of prior knowledge on students' measurement of the heart beat rate in *Daphnia*. When students were confronted with the expectation that certain chemicals were likely to have a given physiological effect on an animal, they seemed willing to report seeing such an effect, even though such a result was impossible.

There are at least two variables that might have confounded the result including lack of skill and lack of veracity in the completion of the measurement task. To address these issues, the study design incorporated a control designed to demonstrate that students do know how to achieve the correct result when their perceptions are not influenced by prior knowledge. This control was the "unknown" (just spring water) that students would have no reason to effect a change when applied to the *Daphnia*. The lack of a statistical difference between the results before and after the administration of the "unknown" shows that the average student teams could make accurate counts of heart rate. It is true that some student teams thought they perceived a stimulation effect and others a depressant effect following the application of the "unknown," most teams reported that the "unknown" had no effect. This is exactly what one would predict when the observers had no reason to anticipate any particular result. The "unknown" was nothing more than pond water and should cause no increase or decrease in heart rate.

Another potentially confounding variable was the possibility that some students wanted to provide the correct result and, therefore, cheated. There is no way to ensure that this did not happen, but the experiment was designed to minimize this effect. Students were told to record whatever they observed no matter what they thought might happen. We responded to any student exclamations of surprise when a result seemed at odds with the expectation by telling them that, sometimes, this might be an individual reaction. Finally, since the students themselves were not assessed and the activity was not part of a graded class assignment, it seemed unlikely that students would be motivated to produce results other than those perceived.

7.7.1 Implications and Recommendations

The implications of these findings are profound and call into question the assumptions science teachers likely make about how well laboratory and other hands-on experiences communicate science content. Thus, there are at least two types of recommendations to be made.

Teachers must no longer assume that because students report the desired results that they really observed what the exercise was designed to demonstrate. By acquainting students with the issue of expectancy, they may be less inclined to fall victim to the problem, or at least will be aware of the limits of observation in general. However, as Rosenthal (1976) found, avoiding the problem is difficult even for professional scientists. Of course, one could suggest that the advantage of expectancy, since students are likely to think that they have seen the desired result even if their work or the design of the activity would have made the teacher-desired result unlikely.

Perhaps doing laboratory work *before* students are fully aware of what is supposed to happen may minimize the expectancy effect. Interestingly, the recommendation that laboratory investigations should precede lecture have been offered for many years (McComas 2005). Also, Boghai (1978), Raghubir (1979), Bishop (1990), Ivins (1985), and Leonard (1980) have shown that this technique is useful in that students exhibit higher levels of cognitive ability, independent functioning, and more fully enjoy laboratory experiences when such activities are more investigatory and less confirmatory than typical ones.

Another interesting issue associated with this activity is the opportunity that it can provide to demonstrate this important effect on students and then engage in a discussion of this aspect of the nature of science. Having students repeat the experiment would be a powerful introduction to the issue of observation and the role of prior knowledge in science generally. Recounting the stories of Millikan and the admonition of Darwin could prove illustrative in this case. Issues that could be discussed might include whether:

- It is even possible to observe a specific phenomenon without expectation of what be seen.
- It is useful to make observations without some expectation or prior speculation.
- Students can operate like scientists while conducting experiments in the school science laboratory.

This last issue was addressed by Hanson (1958) who stated that unless one is trained within a science discipline it is impossible to view the world through the eyes of a scientist. This comment stems as much from the observer-effect as it does from recognition of the controlling paradigm in which the observation was made. When commenting on the ability of a nonscientist to observe a phenomenon, Hanson remarked, “the elements of the visitor’s field, though identical with those of the physicist, are not organized for him as for the physicist” (p. 17).

While it is unlikely that the expectancy effect would cause students to “see” blue litmus paper turn red unless it really did, or report crayfish remnants in the stomach of a dissected frog unless such remains exist. However, in any laboratory or inquiry activity in which subjectivity is involved, expectancy can play a role. Expectancy may complicate exercises that involve almost any sort of measurement such as counting the swings of a pendulum, timing a ball rolling down an inclined plane, titrating, using a color card to determine the pH of a solution, or drawing the line of best fit through a data field.

To conclude, perhaps we should reconsider the admonition of Frances Bacon—one of the forefathers of modern science—that we apply pure induction and observe without bias or preconceptions. We now realize two things making observations in the way recommended by Bacon: (1) it is not possible and even more importantly (2) may not be desirable. As Pasteur said in an 1854 lecture *Dans les champs de l'observation le hasard ne favorise que les esprits prepares.* "Where observation is concerned, chance favors only the prepared mind." What this means, of course, is that prior knowledge is just as valuable in scientific discovery as it is inevitable and potentially challenging, and students must gain understanding about expectancy, confirmation bias, theory-laden observation, and the range of issues that make science a subjective endeavor.

7.7.2 A Note About Ethical Considerations

We recognize the ethical considerations in this kind of research where students were deliberately told an untruth. All teachers involved in the study were aware of its true nature at the beginning, and several indicated that they planned a follow up lesson that would use the result of our investigation as an opportunity to engage student in a discussion of observation. One teacher believed that since the students thought they had seen what they were supposed to have seen, they were better off thinking that they had, in fact, observed the results reported.

It should be clear that no harm could come to the students whether or not they were told the true purpose of the experiment reported here. Those students who were told of the full story would gain a valuable lesson about NOS while those not so informed would still have learned a valuable lesson regarding in the effects of certain chemicals on *Daphnia* physiology.

Acknowledgments I thank the teachers, school administrators, and the hundreds of students who participated as subjects in this investigation and my original coauthor who provided much assistance with the experiment. This chapter has been heavily modified from McComas and Moore (2001) and is used with permission of the publisher of *The American Biology Teacher*.

A. Appendices

Appendix A: The Use of Optical Illusions to Illustrate "Theory-Based" Observations

To illustrate the challenges inherent in "theory-based" observation, instructors may find it useful to secure a wide variety of optical illusions, particularly ones where two images are cleverly blended together in what are sometimes called ambiguous figures. One of these (Fig. 7.1) is the classic often referred to as *Young Woman/Old*

Fig. 7.1 Hill (1915). The classic *My Wife and My Mother-in-Law* ambiguous figure

Woman or *My Wife and My Mother in Law*. The origin of this figure is itself somewhat ambiguous with reports that it first appeared in a different form as a nineteenth century German postcard and was then redrawn by illustrator William Hill and published in the magazine *Puck*. Therefore, it seems reasonable to cite this as Hill (1915).

For those who have not explored this image previously you will have no expectation. Some may first see a young woman who seems to be turning her face to the right. She is wearing a necklace and has a feather on her headscarf. It is just possible to see her left ear and chin, a bit of her left eyelash and her nose. With another look, the image may transform into an older woman who is turning her head somewhat to the left. The necklace of the young woman is now the woman's mouth, the girl's chin is now the nose of the older woman and what was previous the left ear becomes the older woman's eye. They both share a while billowy headscarf, feather, and black hair.

To introduce the topic of "theory-based" observation to students not previously familiar with this image, a teacher could hand out cards to half the students saying, "Do you See the Old Woman in this Image?" and cards to the other half saying, "Do you See the Young Woman in this Image?" and then project the image to the entire class. Then ask the students to raise their hand if they see the Young Woman (or Old Woman, it doesn't matter) and note which hands are raised. Certainly, there will be some who see the "wrong" image, have already seen this picture or can't see either.

Generally, students who were "clued" by the statement on the card to look for the Old Woman will see that image most easily and vice versa. Having a range of such images and related optical illusions ready to share with the class along with two sets of cards directing students to look for different aspects of those images will provide some useful case material to engage students in a discussion of the role of prior expectations in observation. Fortunately, there are many such images available online for use in this fashion.

Appendix B: A Practical Example of Expectancy in Chemistry Class

In a series of lessons in chemistry class students explored some of the variables that affect the rate of gas production during electrolysis. One variable they noted was that the process occurs more quickly as the concentration of the electrolyte increased.

Next, I used this now-prior knowledge to reinforce the technique of electrolysis while introducing some of the problems of observation and thus discuss an important NOS element along with the traditional chemistry content. To extend this lesson and incorporate the expectancy effect, a bit of deceit was necessary.

I made a solution of sodium carbonate and poured that into three different containers. Each container was labeled a different concentration when in fact they were all the equal. I performed a demonstration for the students using a standard electrolysis set-up. I performed the demonstration three times, each with a supposedly different electrolyte solution and asked students to write down their observations. I mentioned the supposed concentration of electrolyte each time I did the demonstration and asked students simply to note anything of interest. They could have noted the time involved and the volume of gas produced if interested or simply watched from a qualitative perspective.

Students in each said things like "Oh wow look at how fast it's going now!" However, the process was going at the same speed every time because the electrolyte concentration was identical in all three trials.

They knew from previous experiments that as the concentration of the electrolyte is increased the electrolysis rate also increases; so many students "saw" what they expected to see. Their expectations caused them to perceive an increase in reaction rate. Had they measured the amount of gas produced and noted the time involved they would have seen that all three trials produced the same amount of gas per unit time.

After the demonstration we had a conversation about the challenges of observation and the expectancy effect. Many of the students were amused that this could happen to them. Although I did hear one student remark, "I didn't think anything special was happening, but everyone was saying it was, so I kept my opinion to myself."

Contributed by Kent Woodard, Chemistry Teacher.
Rogers Arkansas Public Schools.

References

Beveridge, W. I. B. (1957). *The art of scientific investigation*. New York: Norton.

Bishop, R. D. (1990). *The effect of laboratory activity ordering on achievement and retention*. Unpublished doctoral dissertation, Southern Illinois University, Edwardsville.

Boghai, D. (1978). A comparison of the effects of laboratory and discussion sequences on learning college chemistry. *Dissertation Abstracts International, 39*, 6045A.

Boring, E. G. (1950). *A history of experimental psychology* (2nd ed.). New York: Appleton Century Crofts.

Brewer, W. (2015). Perception is theory-laden: The naturalized evidence and philosophical implications. *Journal of general philosophy of science, 46*, 121–138.

Brewer, W. F., & Lambert, B. L. (2001, September). The theory-ladenness of observation and the theory-ladenness of the rest of the scientific process. *Philosophy of Science, 68*(53), S176–S186. https://doi.org/10.1086/392907.

Collette, A. T., & Chiapetta, E. L. (1994). *Science instruction in the middle and secondary schools*. New York: Macmillan Publishing Company.

Cordaro, L., & Ison, J. R. (1963). Observer bias in classical conditioning of the planarian. *Psychological Report, 13*, 787–789.

Darwin, C. R. (1850). *Darwin correspondence project* (www.darwinproject.ac.uk). March 4 letter to Charles Henry Lardner Woodd (DAR 148:375).

Duschl, R. (1985). The changing concept of scientific observation. In R. Bybee (Ed.), *NSTA yearbook: Science, technology and society* (pp. 60–69). Arlington: National Science Teachers Association.

Franklin, A. (1981). Milliken's published and unpublished data on oil drops. *Historical Studies in the Physical Sciences, 11*, 185–201.

Franklin, A. (2015). The theory-ladeness of experiment. *Journal of general philosophy of science, 46*, 155–166.

Gould, S. J. (1994). The geometer of race. *Discover, 15*(11), 67–68.

Gray, D. (1996). Using Daphnia to teach critical thinking about biological research. *The American Biology Teacher, 58*(3), 160–161.

Hainsworth, M. (1956). The effect of previous knowledge on observation. *The School Science Review, 37*, 234–242.

Hainsworth, M. (1958). An experimental study of observation in school children. *The School Science Review, 39*, 264–276.

Hanson, N. R. (1958). *Patterns of discovery*. Cambridge: Cambridge University Press.

Hill, W. E. (1915). *My wife and my mother-in-law*. New York: Puck Press.

Ivins, J. E. (1985). *A comparison of the effects of two instructional sequences involving science laboratory activities.* Unpublished doctoral dissertation, University of Cincinnati, Cincinnati, OH (ERIC Document Reproduction Service, No. ED 259 953).

Johnson, M. L. (1942). Biology and training in observation. *School Science Review, 23*, 56–57.

Lau, K., & Chan, S. (2013). Teaching about theory-laden observation to secondary students through manipulated lab inquiry experience. *Science & Education, 22*, 2641–2658.

Lane, F. W. (1960). *The kingdom of the octopus*. New York: Sheriden.

Leonard, W. H. (1980). Using an extended discretion approach in biology laboratory investigations. *The American Biology Teacher, 42*(7), 338–348.

Mayr, E. (1991). *One long argument*. Cambridge, MA: Harvard University Press.

McComas, W. F. (2005). Laboratory instruction in the service of science teaching and learning. *The Science Teacher, 72*(7), 24–29.

McComas, W. F., & Moore, L. S. (2001). The expectancy effect in the secondary school laboratory: Issues and opportunities. *American Biology Teacher, 63*, 246–252.

Nickerson, R. S. (1998, June), Confirmation bias: A ubiquitous phenomenon in many guises, *Review of General Psychology, 2*(2): 175–220. https://doi.org/10.1037/1089-2680.2.2.175.

Norris, S. (1984). Defining observational competence. *Science Education, 68*(2), 129–142.

Norris, S. (1985). The philosophical basis of observation in science and science education. *Journal of Research in Science Teaching, 22*(9), 817–833.

Raghubir, K. P. (1979). The laboratory investigative approach to science instruction. *Journal of Research in Science Teaching, 16*(1), 13–18.

Rosenthal, R. (1976). *Experimenter effects in behavioral research* (Enlarged Edition). New York: Irvington Publishers.

Rosenthal, R., & Fode, K. L. (1963). The effect of experimenter bias on the performance of the albino rat. *Behavioral Research, 8*, 183–189.

SAPA (*Science – A Process Approach*). (1967). Washington, American Association for the Advancement of Science.

Schindler, S. (2013). Theory-laden experimentation. *Studies in the history and philosophy of science, 44*, 89–101.

Shapare, D. (1982). The concept of observation is science and philosophy. *Philosophy of Science, 59*, 485–525.

Sheldrake, R. (1995). *Seven experiments that could change the world*. New York: Riverbend Books.

Tracy, G. (2018). Learning to see. *American Scientist, 106*(4), 242–249.

Willson, V. L. (1987). Theory-building and theory-confirming observation in science and science-education. *Journal of Research in Science Teaching, 24*(3), 279–284.

Chapter 8
Distinguishing Science, Engineering, and Technology

Gerald Rau and Allison Antink-Meyer

8.1 Introduction

In this chapter, we propose two strategies that demonstrate how science, engineering, and technology are related yet distinct, one of the nine key Nature of Science (NOS) targets. Although vital to the goal of an integrated Science, Technology, Engineering, and Mathematics (STEM) education, this target has been underrepresented in the literature. Understanding how the Nature of Engineering (NOE) relates to NOS will help science teachers incorporate engineering, as required by the *Next Generation Science Standards* (*NGSS*) (NGSS Lead States 2013), and suggest a more effective format for writing up engineering-related lab reports.

NOS research prior to the release of the *NGSS* emphasized characteristics of science knowledge in the context of scientific inquiry (e.g., Lederman et al. 2002). There was mention of the fact that science and technology are related (e.g., Davies and Gilbert 2003; McComas and Olson 1998; Roth 2001), but the distinction between science and engineering was not clear. Although some have written about the connection between science and engineering for many decades (Mitcham 1994), it has only recently become mainstream in conversations about science education.

Science teachers and NOS researchers are undoubtedly familiar with the history of science standards, but may be less familiar with the concomitant development of technology standards. What used to be known as industrial arts education was renamed technology education in 1986 (Lewis and Zuga 2005: 11). This was followed

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_8

by *Technology for All Americans* in 1996 and the first *Standards for Technological Literacy* in 2000, which emphasized the role of technology as design, foregrounding its intimate relationship to engineering (Lewis and Zuga 2005: 12).

Part of the challenge in distinguishing science, engineering, and technology is that the meaning of the word technology has evolved over time. In the past, it was largely synonymous with engineering (Rogers 1983) or pre-engineering (Sanders 2009), but recently it has taken on a restricted meaning of the outcome or product of the disciplines of science and engineering (Arthur 2009), or even more restricted to computers and similar devices (Clough et al. 2013). The multiplicity of definitions makes it hard to know what someone is speaking about when they use the term technology (TAAP and ITEA 2007: 23). This question is beyond the scope of this chapter, so we focus primarily on distinguishing science from engineering.

The *NGSS* recommended the inclusion of engineering in the American science curriculum, but many science teachers feel unprepared to teach it. Of the U.S. high schools surveyed in the 2012 National Survey of Mathematics and Science Education, all required at least 1 year of science credit for graduation, with 64% of reporting high schools requiring at least 3 years, but in most cases engineering courses were not required and did not contribute to science requirements (Banilower et al. 2013). Furthermore, a majority of science teachers reported a lack of preparation for teaching engineering due, in part, to a lack of engineering coursework and experience. Using the strategies proposed in this chapter as part of teacher training or professional development will help overcome this barrier by giving teachers a solid foundation in NOE, which is related to NOS but distinct, as are engineering and science.

There is substantial overlap between NOS and NOE, since science and engineering both involve reiteration and creativity, tentativeness and subjectivity, and are empirically based and socioculturally embedded, but important differences and interactions have rarely been examined in NOS literature. The *distinction* between science as inquiry and engineering as design is the focus of the first strategy described in this chapter, whereas the *interaction* between engineering and science is the focus of the second.

These strategies were developed independently by the two authors and have been used successfully and revised in response to feedback from participants. They could be used individually or jointly with either preservice or in-service teachers.

8.2 Definitions of Science, Engineering, and Technology in U.S. Science Education Documents

Before presenting the strategies, we first examine definitions of science, engineering, and technology in U.S. education documents. While not comprehensive, we believe this provides a reasonable sample to show how the definitions have changed over time. We then propose working definitions based on the current understanding, as reflected in *NGSS*.

Science for All Americans (AAAS 1989) and the *National Science Education Standards* (NRC 1996) both included technology and engineering sections. However, these failed to become integral and assessed components of K-12 science learning.

One of the first national documents to directly address the distinction and connection between the STEM components was *Engineering in K-12 Education* (NRC 2009). The first chapter includes broad definitions of science, technology, and engineering, but the definitions overlap significantly, with science and engineering each described as a body of knowledge and a process. It could even be argued that the definition of technology as the "entire system of people and organizations, knowledge, processes, and devices that go into creating and operating technological artifacts, as well as the artifacts themselves" subsumes both science and engineering under technology (NRC 2009: 17), although the original intent of an "entire system" appears to have been "social structures, as in the technology of electric power or the technology of the Internet" (TAAP and ITEA 2007: 23).

The *Framework for K-12 Science Education* (*Framework*) (NRC 2012) endeavored to clarify the definitions. Although the interaction and mutual support of science and engineering are mentioned several times throughout the document (p. 12, 210–211), the *Framework* also attempts to distinguish the two (p. 51). Moreover, instead of treating engineering and technology as broadly interchangeable, the *Framework* defined engineering as a systematic and often iterative practice for solving problems and technology as the outcome of that practice, a modification of the natural world to fulfill human needs or desires (pp. 11–12, 202).

These definitions are elaborated in the *NGSS* in Appendix I, Engineering Design in the NGSS. There, three elements of engineering design are described which contrast with scientific inquiry. As with scientific inquiry, these elements are not steps that must be followed in a linear manner, but processes that distinguish engineering from science. They are as follows:

A. *Defining and delimiting engineering problems* involve stating the problem to be solved as clearly as possible in terms of criteria for success, and constraints or limits.
B. *Designing solutions to engineering problems* begins with generating a number of different possible solutions, then evaluating potential solutions to see which ones best meet the criteria and constraints of the problem.
C. *Optimizing the design solution* involves a process in which solutions are systematically tested and refined and the final design is improved by trading off less important features for those that are more important (Appendix I, p. 2).

The distinction between science as inquiry and engineering as design is summarized in Appendix F, Science and Engineering Practices 1 and 6:

> 1. Asking questions (for science) and defining problems (for engineering).
> 6. Constructing explanations (for science) and designing solutions (for engineering).
> (Appendix F, p. 1)

Throughout the *NGSS*, the "interdependence of science, engineering, and technology" and "influence of engineering, technology, and science on society and the natural world" are frequently mentioned. In Appendix H, which specifically addresses NOS, engineering is always mentioned as the second part of "science and engineering practices," with no clear distinction made between the two. Ultimately, the *NGSS* are *science* standards, and do not endeavor to "put forward a full set of standards for engineering education, but rather include only practices and ideas about engineering design that are considered necessary for literate citizens" (Appendix I, p. 3).

In conclusion, based on these documents we offer the following as working definitions which reflect the current understanding of "engineering as a systematic practice for solving problems, and technology as the result of that practice" (NGSS, Appendix I, p. 2):

> **Science** involves asking questions and constructing explanations, using a systematic approach to develop models, carry out investigations, analyze and interpret data, and argue from evidence to understand the natural world.
> **Engineering** involves defining problems and finding solutions, using a systematic and often iterative approach to design products, processes, and systems to meet human needs and wants.
> **Technology** is any modification of the natural world made to fulfill human needs or desires, comprising all types of human-made products, processes, and systems, including those that extend our senses or abilities and thus facilitate science and engineering.

Since it is clear that by the current definitions, science and engineering are disciplines with a particular focus and approach, whereas technology is not, the rest of the chapter will focus on science vs. engineering, with only minor mention of the role of technology.

8.3 Two Strategies for Teacher Training

The remainder of the chapter is devoted to description of two strategies that will give readers first-hand knowledge of how science, engineering, and technology are distinct but related. After an overview of the activities, details are presented in two subsections, followed by a conclusion summarizing how they can support integration of engineering into K-12 science classrooms.

The first strategy will help preservice or in-service teachers distinguish science from engineering and concurrently demonstrate how students should structure reports on projects or labs that incorporate engineering concepts (engineering lab reports), based on an analysis of the format of engineering research articles. The activity has been used by the first author as the first step in teaching graduate students in science and engineering the difference between research articles published in the two disciplines. It will be useful for either graduate students in science education or in-service science teachers, and can be completed in 2–3 h.

The second strategy supports science teachers' conceptions of the interrelationships between technology, engineering, and science in modern research. Developed by the second author, it uses a framework based on the science and engineering practices in the *NGSS* and comparison of paired research to help teachers understand the epistemic similarities and differences between the two. Optional activities explore engineering design challenges. This strategy, which can be completed in 6–8 h, has been successfully used in its entirety with in-service teachers in an online environment, and is likewise amenable to preservice teachers or classroom settings.

8.3.1 Strategy One: Distinguishing Science and Engineering

When first year graduate students in engineering are asked what format is used by journals in their field, many students have no clue, while a few say they follow Introduction, Methods, Results, Discussion (IMRD). This is a common misconception found in books on scientific writing and undoubtedly held by many science teachers as well. The components included in the two are similar, but there are enough differences in section titles and the organization and emphasis of those components that a separate name has been proposed for the engineering format: Introduction, Process, Testing, Conclusions (IPTC) (Rau 2019). This is important for science teachers because the difference in the way information is communicated reflects the distinction between the construction of explanations in science and the design of solutions in engineering.

The strategy consists of four stages, as shown in Table 8.1. The second stage elucidates the key conceptual idea that science teachers must understand, while the last shows how to incorporate that knowledge into their classes.

8.3.1.1 Stage 1: Reveal Misconception That Engineering Articles Follow IMRD

The first stage of the activity begins with participants comparing the format of journal articles presenting original research in various fields of science and engineering. Each participant is asked to list the section and subsection titles of one article, and then compare lists. Students are inevitably surprised to observe that although

Table 8.1 Brief description and purpose of each stage of strategy 1

	Description	Purpose
Stage 1	Compare section titles of science and engineering research articles	Reveal misconceptions about structure of engineering articles
Stage 2	Compare division length in science and engineering research articles	Discover focus of engineering vs. science research
Stage 3	Compare components of science and engineering research articles	Discover similarities and differences between engineering and science research
Stage 4	Closing discussion	Pedagogical implications for writing engineering lab reports

Table 8.2 Divisions in IPTC format, showing the similarity to sections in modified IMRD

IMRD (modified)	IPTC
Introduction	Introduction
Materials and methods	Product or process
Results and discussion	Testing
Conclusion	Conclusion

science articles from a number of fields use IMRD (often modified with combined R&D plus Conclusion), most engineering articles do not follow that format and frequently contain six to eight sections. Engineering articles almost invariably begin with an Introduction and end with a Conclusion, but many of the other sections have titles specific to the research, so there is great diversity between articles.

Following this, the structure of the IPTC format is presented, and the similarity to modified IMRD, as shown in Table 8.2. Participants with an article in IPTC format are asked to determine which section or sections describe testing of the new design, whether physical or simulation, and label those the Testing *division* (a term used to distinguish the general conceptual division from the specific names of the *sections* of the article, which for this division frequently include “Experiment,” “Verification,” “Comparison,” “Results,” “Analysis,” or similar words). Although many engineering articles use the term “Experiment,” it is exceedingly rare that the tests conducted constitute a true experiment, with experimental and response variables, control, and replication. Usually the tests are a comparison of the new design with either the current standard or a mathematical ideal, without replication or statistics. Thus the division name Testing has been chosen in an attempt both to represent the diversity of testing procedures and to promote basic NOS literacy. All remaining sections between the Introduction and the Testing division are labeled the Product or Process division, as they will describe the design of one or the other (rarely both).

8.3.1.2 Stage 2: Focus of Science and Engineering Articles

In the second stage, participants are asked to determine the relative length of each division, either by counting the number of paragraphs or the number of pages. The latter is particularly useful if there are many tables, figures, or mathematical expressions, or if the articles are very long. Comparing results, they will note that in IMRD, the Results section often accounts for 50% of the article, whereas in IPTC, half of the article may be in the Process division, revealing a difference in the focus of the work. This is shown diagrammatically in Fig. 8.1. The reason for the difference in shape will be explained below.

After participants are given time to speculate on possible reasons for the difference, an explanation is presented. Based on the science practices in Appendix F of the *NGSS*, science asks questions and constructs explanations, while engineering defines problems and designs solutions. Since science and engineering have different goals, the focus of research articles in the two also differs, as shown in Table 8.3. This is the main conceptual point of the activity, and parallels the identical conclusion in Stage 2 of the second strategy.

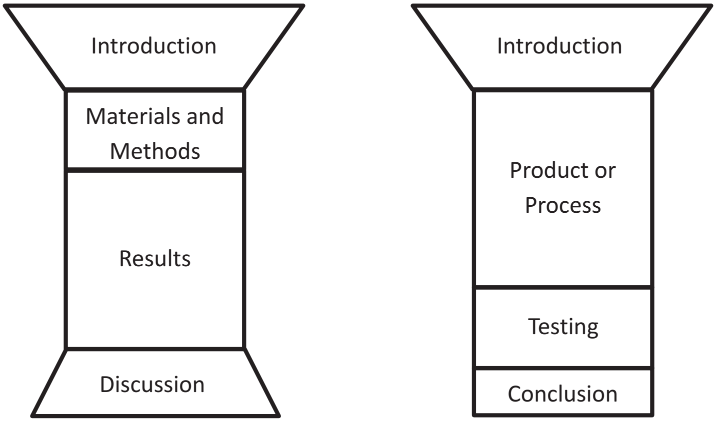

Fig. 8.1 Relative length and shape of divisions in IMRD and IPTC formats (from Rau 2019)

Table 8.3 Summary of the focus of each division in IMRD and IPTC formats (modified from Rau 2019)

IMRD division	**Focus**
Introduction	Questions to be addressed by the *data*
Material and methods	How the *data* were generated
Results	Summary of the *data*
Discussion	Explanation of the *data*
IPTC division	**Focus**
Introduction	Problem to be addressed by the *design*
Process or product	Solution proposed by the *design*
Testing	Comparison with previous *design*
Conclusion	Advantage of the *design*

Since a prototypical science paper focuses on the data generated to answer a question, the Results section, where data are summarized, is usually the longest. On the other hand, in a prototypical engineering paper more space is devoted to description of the new design being proposed to solve the problem. Some fields are exceptions, as will be noted below.

8.3.1.3 Stage 3: Similarities and Differences Between Science and Engineering

In the third stage, ten common components found in both science and engineering articles are described (Table 8.4), then participants are asked to find where each occurs in their articles. These components were identified and descriptions modified over the years based on feedback from science and engineering graduate students. Participants will see that while science and engineering make similar basic claims, the organization and the emphasis given to each differ greatly. This is the most

Table 8.4 Ten common components of science and engineering research articles (from Rau 2019)

Component	Subcomponents common in science and engineering
1. Importance	This research is important to society
	This topic is important to researchers in the field
2. Need	A gap exists in current knowledge or understanding (IMRD)
	The current best solution is limited or less than ideal (IPTC)
3. Research goal	We answer a question or improve understanding (IMRD)
	We propose a better solution to a problem (IPTC)
3. Research goal	We answer a question or improve understanding (IMRD)
	We propose a better solution to a problem (IPTC)
4. Framework	The research is based on an accepted model or framework
	This is the best model or method to follow for our research
5. Research details	Care was taken to ensure good results (IMRD)
	A workable solution was developed (IPTC)
6. Testing methods	We can predict results based on the model
	Testing followed verifiable procedures
7. Data patterns	A pattern can be discerned in the data
	Exceptions to the pattern can be identified
8. Comparisons	Data [support/question] previous work
	Data [conform to/differ from] expectations
9. Interpretations	Data are best interpreted in a certain way
	There is a reasonable cause for the data
10. Conclusion	The question has been answered or the aim achieved
	The solution is an improvement on the current best design

time-consuming part of the activity, as participants must go through the whole article and have time to discuss their findings with one another.

Students can identify the location of components in their article on their own, but if they are reading an article in an unfamiliar field, giving them Table 8.5 first and asking if their article matches the "typical" pattern will speed the process. It must be

Table 8.5 Typical location of ten common components of science and engineering articles in IMRD and IPTC format research articles (from Rau 2019)

IMRD (Science)		IPTC (Engineering)	
Section	Components	Division	Components
Introduction	Importance	**I**ntroduction	Importance
			Need
	Need		Research goal
	Research goal		
	Framework		
	Research details	**P**roduct or process	Framework
Materials & methods	Testing methods		Research details
		Testing	Testing methods
			Data patterns
Results	Data patterns		Comparisons
Discussion	Comparisons		Interpretations
	Interpretations		
	Conclusion	**C**onclusion	Conclusion

emphasized that the location is quite variable from field to field, and even from journal to journal within a field. Note the similarity of order, but that the division structure differs.

Both formats usually begin the Introduction by establishing the importance of the research field. The Introduction then narrows, including sufficient information on previous research to establish the need for the present work. In IMRD the choice of theoretical framework may be justified here as well. In IPTC the Introduction may be as short as one paragraph or over a page long including tables or figures. The research goal, whether stated as a question, a problem, or a proposed solution, is usually found in the last paragraph of the Introduction, or penultimate if the last paragraph gives an overview of the rest of the article, as is common in IPTC.

Details of how the research was carried out appear in the second division in both formats, but the purpose and extent are quite different. In IMRD the Methods are often written in a very condensed style, almost a list. Their purpose is to validate the research by showing that the materials were obtained from reputable suppliers and the data were collected in a reliable way. The tests to be done, including experimental design, hypothesis testing, and statistical procedures, figure prominently in quantitative research. In IPTC the Process division is the longest in the paper, giving a detailed descriptive analysis of the design and the design process, in a style more similar to qualitative research. Most fields of engineering do not require statistics, as no attempt is made to generalize the results, but may include sections containing extensive mathematical formulas, algorithms, proofs, models, or simulations.

Further differences appear in the third and fourth divisions. In IMRD, the Results typically comprise an extensive summary of the data, with minimal commentary. Hypothesis testing and comparison of the results with predictions may be in the

Results, but comparison with other studies along with interpretation is left for the Discussion section. In the final paragraph, the authors frequently mention potential applications of the work or future work, leading to the broadening in the typical "hourglass" structure. In IPTC, description of how the new design will be tested, either against extant designs or some theoretical optimum, is usually immediately followed in the same section, often even in the same paragraph, by the results of the test and their interpretation, comprising the Testing division. The Conclusion is usually a one or two paragraph statement of the contribution of the work, without any comment on applications or future work, thus without broadening (Fig. 8.1).

8.3.1.4 Stage 4: Pedagogical Implications

A fourth stage, discussion of pedagogical applications, closes the activity. The most obvious application is the writing of laboratory reports on engineering-related topics in science classes, for example design challenges. If an assignment is basically an engineering project, it makes little sense to try to squeeze the report into IMRD format. Whether the division titles IPTC are used or whether descriptive titles are given for the middle two divisions would be a choice the teacher or students could make. The comparisons of science and engineering formats (Fig. 8.1 and Table 8.3) may be useful to students in understanding the difference between science and engineering research, while the list of common components and their typical locations (Tables 8.4 and 8.5) may be helpful in organizing their reports. It should be obvious to teachers that some components, particularly 1–3, may be absent and all will be substantially modified, as they are in science lab reports (Parkinson 2017).

8.3.1.5 Practical Considerations

The first three stages can be done in pairs, but it is beneficial to have participants work in groups of 4–6, with an equal number of IMRD and IPTC articles in each group, so they can make generalizations about the format of each. Examination of the structure of IPTC articles in Stage 1 may be done cooperatively in these groups so those with IMRD articles can also benefit. The same articles may be used for each group, or a larger selection of articles may be used from different fields. The advantage of the former is less preparation time for the instructor and greater predictability, while the advantage of the latter is a wider representation. There is a great degree of variation from journal to journal, even within electrical engineering, so a larger sample gives a better picture of that variability. It is also important to note that some science fields, like physics, often employ IPTC format, while some engineering fields, like chemical engineering and materials science, frequently follow a modified IMRD format. Most electrical and mechanical engineering articles are good examples of the IPTC format. When choosing the articles, make sure that only original research articles are included, not brief reports, review articles, or overview of standards, each of which has its own format. Finally, this activity is designed as a participatory inquiry, thus while the overall pattern is predictable there will undoubtedly be articles that do not fit, which can lead to further inquiry if time allows.

8.3.2 Strategy Two: The Interrelationships between Science, Engineering, and Technology

The explicit, reflective strategy described in this section helps science teachers develop informed conceptions about the interrelationships between technology, engineering, and science in modern research. Originally developed as an asynchronous online professional development (PD), the following strategy provides an experience for K-12 science teachers to examine the overlap between scientific inquiry and engineering design, and ultimately reflect on the role of technology in each.

The strategy consists of six stages, as shown in Table 8.6. The fifth and sixth stages are not essential to the strategy. However, for in-service science teachers they support the translation of understanding into classroom changes. Intentional support is necessary as even science teachers with informed NOS conceptions do not necessarily teach for NOS understanding among their students (Abd-El-Khalick et al. 1998).

8.3.2.1 Stage 1: Reveal Prior Conceptions About Science, Engineering, and Technology

The first stage consists of a series of questions to capture prior conceptions. While not exhaustive, these questions provide information about how participants view technology, engineering, science, and their relationship in a research context.

Table 8.6 Brief description and purpose of each stage of strategy 2

	Description	Purpose
Stage 1	Reflective prompts	Reveal prior conceptions about science, engineering, and technology
Stage 2	Online lecture on relative emphasis of science and engineering	Comparison of science and engineering based on *NGSS* science practices
Stage 3	Compare written and video summaries of science and engineering research	Discover similarities and differences between engineering and science research
Stage 4	Audio reflection	Reveal remaining misconceptions
Stage 5 (optional)	Design challenge	First-hand understanding of engineering design
Stage 6 (optional)	Classroom video analysis	Pedagogical implications for conducting engineering design

1. What is science? Provide a brief definition and give an example of a scientist or scientific investigation that you are familiar with in order to support your definition.
2. What is engineering? Provide a brief definition and give an example of an engineer or engineering project that you are familiar with in order to support your definition.
3. What is technology? Provide a brief definition and give an example of someone whose work can be described as relating to technology or a technology project that you are familiar with in order to support your definition.
4. Are science, engineering, and technology related to one another? If yes, describe the ways in which they are related.
5. What role do questions and problem solving play in science? In engineering?
6. What role does creativity play in science? In engineering?
7. What role do data play in science? In engineering?
8. What role does communication play in science? In engineering?
9. How do the methods of science and the methods of engineering compare to one another?

These are completed in a journal or questionnaire format and are also used as discussion prompts.

8.3.2.2 Stage 2: Comparison of Science and Engineering based on NGSS

Although science and engineering practices are both identified in the *NGSS*, specific distinctions between them are not well articulated. The second stage of the strategy involves instruction about these practices through the lens of Cunningham and Carlsen's (2014) framework of the relative emphases of science and engineering (Table 8.7), showing them to be distinct but related.

8.3.2.3 Stage 3: Similarities and Differences between Science and Engineering

The third stage of the strategy consists of current research projects, presented through one video and one reading each. Projects are selected based on three criteria: (1) they are potentially interesting to a non-scientist/non-engineer audience, (2) at least one video and one reading resource exist that are accessible to a non-specialist and present sufficient information to understand the nature of the research (e.g., TED talks/New Scientist), and (3) the implications of the research are similar to another project selected. The projects are presented in pairs, as in Table 8.8, to prompt teachers to compare science and engineering practices.

Using both the video and the reading, participants are asked to infer whether the practices in each project are more relevant to science or to engineering. They are then asked to submit an audio file reflecting on the specific skills and tools the

Table 8.7 Relative emphases of science and engineering, based on *NGSS* science practices (Reproduced from Cunningham and Carlsen 2014)

Next Generation Science Standards practice	Relative emphasis in science	Relative emphasis in engineering
1. Asking questions and defining problems	The goal of this practice in science is to make theoretical and conceptual progress	The goal of this practice in engineering to is create useful, novel technology
2. Developing and using models	Models are used to explain and predict in science	Models are used to analyze and evaluate in engineering
3. Planning and carrying out investigations	Scientific investigations use a variety of methods including hypothesis testing	Investigations in engineering typically evaluate designs/ technology
4. Analyzing and interpreting data	Empirically based information about the found, natural world	Criteria based: e.g., materials properties, risk of failure, cost
5. Using mathematics and computational thinking	Evaluating conceptual models against collected data	Designing things using both real and simulated data
6. Constructing explanations and designing solutions	Objective is to develop a single "best" explanation	Objective is preferred design, selected from among alternatives, with explicit consideration to trade offs
7. Engaging in argument from evidence	Peer review process includes persuading peers	Client-based process includes satisfying a client
8. Obtaining, evaluating, and communicating information	Free exchange of information, creativity is supportive in all aspects of information	Legal propriety, creativity critical

researchers use in their work. Unlike a document, which can easily be edited and refined, an audio file provides additional information through vocal inflection, hesitation, and tone.

8.3.2.4 Stage 4: Reveal Remaining Misconceptions

The fourth stage of the strategy involves written facilitator feedback and participant response. Initial feedback is primarily in the form of questions about participants' audio reflections. Using the practices and relative emphases introduced in stage two, evidence of misconceptions is identified and questions posed that ask participants to explain their position. Some misconceptions have been described elsewhere (Antink-Meyer and Meyer 2016). Additional common misconceptions that we have seen emerge in teachers' reflections include the following ideas: (1) mechanical or civil engineering work is viewed as engineering, but biomedical or materials engineering is not; (2) failure to understand the relationship between defining problems and designing solutions in engineering, or between asking questions and constructing explanations in science; (3) digital tools are considered to be technology but low-tech artifacts (e.g., syringes, cooling techniques, and procedures) are not.

Table 8.8 Example of paired science and engineering research

Science project (Vampire Mice)		Engineering project (Tissue Engineering)	
Video	Reading	Video	Reading
Wagers (2010)	Coghlan (2014)	Tandon (2012)	Cheung (2013)
https://www.technologyreview.com/s/417249/young-blood-reverses-signs-of-aging-in-old-mice/	https://www.newscientist.com/article/dn25516-blood-protein-rejuvenates-brain-and-muscle-in-old-mice/	https://www.ted.com/talks/nina_tandon_could_tissue_engineering_mean_personalized_medicine	https://www.newscientist.com/article/mg22029440-800-grow-your-own-organs-as-a-tissue-engineer/

8.3.2.5 Stage 5: Understanding Engineering Design

The fifth stage is optional but useful for science teachers lacking formal technology or engineering education. Technology is the product of the overlap between science and engineering, thus a purposeful experience with technology is important to this strategy. Stage 5 is designed to provide an experience with selecting, critiquing, and utilizing technology in an engineering design challenge. Participants are provided with four design challenge contexts to choose from, each with design criteria to meet. The challenges do not provide protocols for the development of specific designs, or required technologies that must be used or developed, although each suggests potentially useful technologies (e.g., light emitting diodes [LEDs], battery packs, multimeters, three-dimensional [3D] printers, and glassware). Instead, the purpose is for teachers to experience optimization, failure, and prototyping in ways that draw on existing technologies and their understanding of science concepts. Biomimicry, robotics, circuits, structures, and gastronomy design contexts have each been used with success (Antink-Meyer and Meyer 2016; Halverson and Sheridan 2014). Participants record images (hand drawn sketches, video, or still images) at three different times, and submit an audio reflection on prompts. Some examples of prompts are:

1. Identify the technologies you used and/or developed in the design challenge.
2. Describe how (and whether) developing and using models was a practice that you experienced. Did you have an idea you were testing out? Was there a basis, or model, that you were drawing on?
3. Describe how (and whether) planning and carrying out investigations was a practice you experienced in your project. Did you evaluate the directions given, the process as you carried it out, or the design as you understood it?
4. Describe how (and whether) you analyzed and interpreted data. What kind of information were you consciously and unconsciously gathering as you proceeded? Did you make changes as you went dependent on how the project was emerging?
5. Describe how (and whether) you constructed explanations and designed solutions. Did you run into any road blocks, what were they, how did you try to solve them, and to what extent were you successful?
6. Based on your experience in the project you chose, what are the cognitive challenges associated with classroom-based engineering tasks?
7. Based on your experience in the project you chose as well as in your teaching experience, what are the affective challenges associated with classroom-based engineering tasks?
8. What, if any, examples of what you consider "scientific" knowledge did you use? Engineering knowledge? Technology knowledge?

The design challenges provide experience with tangible contexts that depend on existing technologies, the modifications of technologies, and knowledge of science concepts in order to provide an opportunity for reflection on how science, engineering, and technology overlap. Without this stage, characteristics of scientific knowledge and engineering have little logical overlap for most teachers, although creativity, tentativeness, subjectivity, and empirical dependence are important aspects of both NOS and NOE. The purpose in this stage is to support reflection on the ontological underpinnings, showing that despite the distinction between them, interdependence is an important result of that distinction.

8.3.2.6 Stage 6: Pedagogical Implications

The sixth stage of the strategy is also optional but supportive of classroom practice. Links are provided to four videos of classroom teaching of engineering design challenges, along with an observation protocol based on the learning progressions in *NGSS* (Antink-Meyer and Meyer 2016). Participants identify and describe the science or engineering practices observed in each video, then respond to the following prompts in either an audio or written reflection.

1. To what extent did you observe students learning both subject matter and developing the abilities associated with the practices?
2. Were there aspects of each lesson that you felt could have been improved in order to make the lesson more effective?
3. If you were to use that lesson with your students, what challenges do you think you would encounter and what modifications would you make?
4. Compare one of the lessons you observed to the engineering design challenge you completed. How did the skills, challenges, and technologies you encountered compare to what you can infer the students encountered from the video?
5. Think about the research examples you examined. To what extent do the videos show classrooms that will foster technology, science, and engineering literacy, interest, and talent such as that demonstrated among the researchers from the readings and videos?

The purpose of this stage is to support reflection on how participants can connect their new understanding to K-12 classrooms. The facilitator's responses to participants' reflections are critical in supporting science teachers' conceptions of technology, engineering, and science. The desired outcomes for teachers are conceptions that align with Cunningham and Carlsen's relative emphases of science and engineering practices and recognize the importance of technology to science and engineering.

8.4 Summary and Conclusion

Comparison of Tables 8.1 and 8.6 shows that there is considerable overlap between the two strategies, particularly in the purpose and concepts addressed by the first three stages of each. Integrating the two strategies could potentially take a variety of forms, depending on the time available and the background and needs of the participants. Both strategies support teachers' understanding of the distinction and overlap between engineering and science, with less emphasis on the role of technology. Use of these strategies with pre-service or in-service science teachers will promote incorporation of engineering into science curriculum and assessment.

Many science teachers, particularly in physical science and physics, undoubtedly already incorporate elements of engineering education into their classes. These may be called design challenges, problem-based learning, or purposeful design and inquiry. Teachers of biology and chemistry may consider it more difficult to incorporate such methods. It is not a coincidence that many physics research articles are written in IPTC format, but chemical and biomedical engineering prefer IMRD. Our common demarcation between science and engineering does not correspond perfectly with the demarcation in research methods.

Just as school science is not the same as true research science, these school engineering projects differ in important ways from true engineering. Nevertheless, if they are open-ended and engaging, they can encourage the type of thinking employed by engineers just as inquiry-based science education aims to encourage scientific thinking. Using a laboratory report format appropriate to the activity will further support this goal.

Use of these strategies will also undoubtedly reveal more misconceptions about NOE, a necessary starting point for conceptual change. We hope this chapter will spur further work on the history, sociology, and philosophy of engineering, particularly as it relates to science education, thus promoting a more complete understanding of the relationship between NOS and NOE.

References

Abd-El-Khalick, F., Bell, R. L., & Lederman, N. G. (1998). The nature of science and instructional practice: Making the unnatural natural. *Science Education, 82*(4), 417–436.

American Association for the Advancement of Science. (1989). *Science for all Americans: Project 2061*. New York: Oxford University Press.

Antink-Meyer, A., & Meyer, D. Z. (2016). Science teachers' misconceptions in science and engineering distinctions: Reflections on modern research examples. *Journal of Science Teacher Education, 27*(6), 625–647.

Arthur, W. B. (2009). *The nature of technology: What it is and how it evolves*. Simon and Schuster.

Banilower, E. R., Smith, P. S., Weiss, I. R., Malzahn, K. A., Campbell, K. M., & Weis, A. M. (2013). *Report of the 2012 National Survey of science and mathematics education*. Chapel Hill: Horizon Research, Inc.

Cheung, A. (2013). Grow your own organs as a tissue engineer. Careers. *New Scientist*. https://www.newscientist.com/article/mg22029440-800-grow-your-own-organs-as-a-tissue-engineer/. Accessed 5 Dec 2016.

Clough, M. P., Olson, J. K., & Niederhauser, D. S. (2013). *The nature of technology: Implications for learning and teaching*. Dordrecht: Springer.

Coghlan, A. (2014). Blood protein regenerates brain and muscle in old mice. Daily News. *New Scientist*. https://www.newscientist.com/article/dn25516-blood-protein-rejuvenates-brain-and-muscle-in-old-mice/ . Accessed 5 Dec 2016.

Cunningham, C. M., & Carlsen, W. S. (2014). Teaching engineering practices. *Journal of Science Teacher Education, 25*(2), 197–210.

Davies, T., & Gilbert, J. (2003). Modelling: Promoting creativity while forging links between science education and design and technology education. *Canadian Journal of Math, Science & Technology Education, 3*(1), 67–82.

Halverson, E. R., & Sheridan, K. (2014). The maker movement in education. *Harvard Educational Review, 84*(4), 495–504.

Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., & Schwartz, R. S. (2002). Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching, 39*(6), 497–521.

Lewis, T., & Zuga, K. F. (2005). *A conceptual framework of ideas and issues in technology education*. Arlington: Technology Teacher In-service Education & National Science Foundation.

McComas, W. F., & Olson, J. K. (1998). The nature of science in international education standards documents. In W. F. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 41–52). Dordrecht: Kluwer Academic Publishers.

Mitcham, C. (1994). *Thinking through technology: The path between engineering and philosophy*. Chicago: University of Chicago Press.

National Research Council (Ed.). (1996). *National science education standards*. Washington, DC: National Academy Press.

National Research Council. (2009). *Engineering in K-12 education: Understanding the status and improving the prospects*. National Academies Press.

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. National Academies Press.

NGSS Lead States. (2013). *Next generation science standards: For states, by states*. Washington, DC: National Academies Press.

Parkinson, J. (2017). The student laboratory report genre: A genre analysis. *English for Specific Purposes, 45*, 1–13.

Rau, G. (2019). *Writing for science and engineering students: Staking your claim*. London: Taylor & Francis.

Rogers, G. F. C. (1983). *The nature of engineering: A philosophy of technology*. The Macmillan Press-Ltd.

Roth, W. M. (2001). Learning science through technological design. *Journal of Research in Science Teaching, 38*(7), 768–790.

Sanders, M. (2009). STEM, STEM education, STEMania. *The Technology Teacher, 68*(4), 20–26.

Tandon, N. (2012). Could tissue engineering mean personalized medicine? Video file. *TED Talks*. https://www.ted.com/talks/nina_tandon_could_tissue_engineering_mean_personalized_medicine. Accessed 5 Dec 2016.

Technology for All Americans Project, & International Technology Education Association. (2007). *Standards for technological literacy: Content for the study of technology, 3rd edition*. Reston: International Technology Education Association.

Wagers, A. (2010). Young blood reverses signs of aging in old mice. Video file. *MIT Technology Review*. https://www.technologyreview.com/s/417249/young-blood-reverses-signs-of-aging-in-old-mice/. Accessed 5 Dec 2016.

Part III
Teaching About Nature of Science: Generalized Instructional Perspectives

Chapter 9
The Use of Metacognitive Prompts to Foster Nature of Science Learning

Erin E. Peters-Burton and Stephen R. Burton

Building students' knowledge of the nature of science (NOS) has potential to improve important elements of science literacy as students learn both a body of scientific knowledge and develop understanding of how that body of knowledge has come to be (Duschl 1990; Peters and Kitsantas 2010a). Over 20 years of evidence has demonstrated that a person's epistemology plays a role in developing reasoning, connecting evidence and claims, and setting the foundation for learning approaches (Hofer and Pintrich 1997; King and Kitchener 1994). Therefore, an emphasis on teaching NOS in science class is important in developing scientifically literate students. However, teaching a sophisticated understanding of NOS to students has been difficult in part due to unfocused pedagogical approaches offered to teachers. The incorporation of NOS teaching into inquiry-based lessons can be focused by a learning theory, and self-regulated learning theory (SRL) has potential as a helpful tool for incorporation of NOS because the theory explains learning as a goal-directed process whereby a person is required to identify a problem, examine relevant data to inform a solution, develop a solution, and evaluate the solution (Zimmerman 2008). The approach offered in this chapter presents new opportunities to reach students supported by a well-document learning theory.

SRL describes how learners react to their learning environment with their currently held beliefs, values, knowledge, motivation, and metacognitive strategies. According to SRL theory, individuals are not merely passive players in the learning process; rather, they have the potential to exert personal agency and control over their learning goals. Self-regulated learners enter three phases of a learning cycle: forethought, performance, and self-reflection (Zimmerman 2000) as illustrated in

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_9

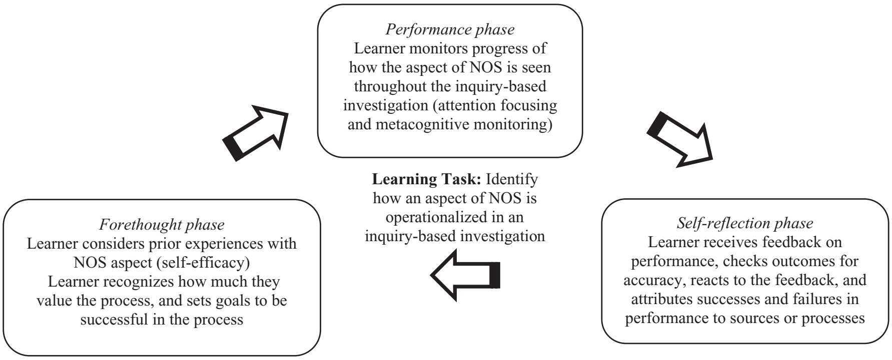

Fig. 9.1 Self-regulated learning (SRL) in an aspect of NOS during an inquiry-based activity. (Adapted from Zimmerman 2000)

an NOS teaching context in Fig. 9.1. The forethought phase refers to influential processes that precede efforts to act and set the stage for action such as analyzing tasks and setting process-oriented goals. The performance phase includes processes that occur during the action, such as implementation of the task and metacognitive monitoring. The self-reflection phase refers to the processes that occur after the performance efforts which influence a person's response to the action, such as the use of standards to make self-judgments about the performance. Students continue to cycle through the self-regulation feedback loops each time they encounter a learning task, and if they have helpful learning strategies, such as setting a learning goal that is accurate and achievable and monitoring their performance against that goal throughout a cycle, they develop more sophisticated forethought, performance, and self-reflection processes. If learners use detrimental learning processes, such as having low self-efficacy or setting vague goals that are not aligned with the teacher's learning goals, they can develop bad habits in terms of learning strategies and decline in their academic performance (Zimmerman 2008). Although self-regulatory processes are internally driven, they can be encouraged by mentors or an appropriately constructed learning environment (Zimmerman 2000), thus allowing a teacher to serve as a model to teach how NOS is present in scientific investigations in a directed way. Across most academic skill areas and content domains, such as reading, mathematics, writing, and science, the literature shows that SRL processes (e.g., planning, strategy use, monitoring, and evaluation) are key determinants of students' achievement (Butler et al. 2005; Cleary and Platten 2013; De Corte et al. 2011; Graham and Harris 2005; Guthrie and Wigfield 2000; Sinatra and Taasoobshirazi 2011).

The focus on teaching through explicit and reflective methods has shown promise in improving views of NOS (Khishfe and Abd-El-Khalick 2002). These explicit, reflective approaches are focused on what the teacher should do, not on what students should be doing to learn NOS. Various learning theories are helpful in designing efficient and effective student-centered curricula and instruction (Driscoll 2000), but SRL theory aligns particularly well with approaches to learn NOS in the classroom because the theory is goal oriented and reflective, much like explicit and reflective methods. The application of SRL to NOS learning during guided inquiry lessons has been tested and found to result in improved student NOS and science content learning (Peters-Burton 2015, 2017; Peters and Kitsantas 2010b). Because SRL is more detailed in explaining the processes of learning and motivation than current approaches to teaching NOS, it offers distinct ways to support learner strategies that include affective, motivational, and cognitive factors.

9.1 Architecture of a Teaching Strategy for Teaching NOS

The strategy presented in this chapter is called Metacognitive Promoting Intervention-Science (MPI-S) and is based on a teaching strategy derived from SRL with an emphasis on learner actions (Peters 2009; Peters and Kitsantas 2010b). MPI-S enacts SRL because it prompts students to set goals, assists students in monitoring progress toward goals, and asks students to reflect on their success in reaching those goals. This teaching strategy works well for inquiry lessons because it engages students with the processes and approaches to thinking of science. MPI-S is a suite of curricular tools, made up of a suite of checklists and questions that can be incorporated into established lesson plans to support student SRL strategies. The implementation of MPI-S consists of four steps as seen in Fig. 9.2. The steps of MPI-S are the same ones as the coaching strategy founded by Zimmerman (2000) and have identical names as Zimmerman's strategy. Although MPI-S has been used to develop NOS views in students, the metacognitive prompts can also be used for learning about other science components such as content knowledge and practices in science.

This approach parallels explicit, reflective approaches because the teacher initially supports students explicitly through modeling and then drops the level of support so that students are able to articulate how they understand NOS independently (akin to scaffolding). MPI-S should be implemented in an inquiry-based setting, since the teaching focuses on student use of science process skills that are tangible. Evidence of the effectiveness of this teaching strategy was found with eighth grade students using MPI-S. Students went back to elaborate on their observations to be more aligned to the checklist (Peters 2009).

9.1.1 Modeling

Modeling is the first step in the MPI-S teaching strategy and is aligned to the forethought processes of SRL (Fig. 9.2). Since students are often underexposed to the ways scientists think and conduct their work (Hogan 2000), it is important that students begin a learning task by understanding the goal they are trying to reach. The modeling step in MPI-S helps students with their forethought processes because

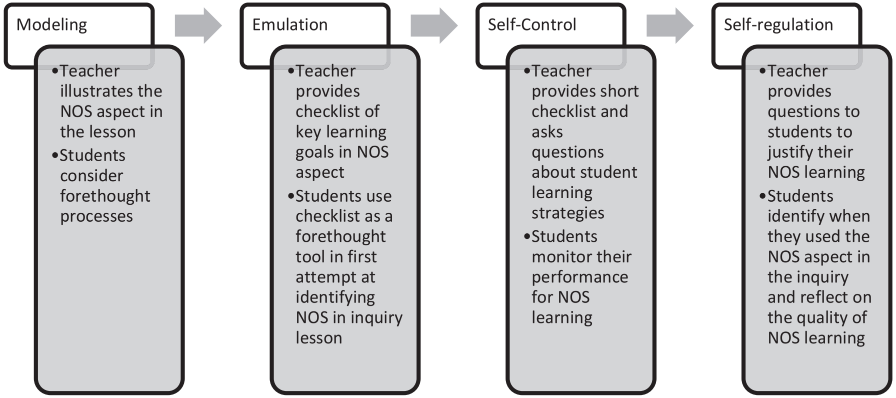

Fig. 9.2 Steps of MPI-S with teacher role and student SRL processes

it demonstrates their learning goal, and helps them evaluate their self-efficacy and value in the task. In MPI-S, students learn what outcome is expected through teacher modeling. Modeling is much like a cognitive apprenticeship (Collins et al. 1987) where the mentor (teacher) does the activities in full view of the apprentice (students), but at the same time talks aloud about rationale, choices, and decision points with the intention that the apprentice will be able to adopt the same practices. For example, a teacher can demonstrate how she would record observational data that was replicable, because the recorded observations were expressed in standardized notation such as metric measurement. The role of the student in this first step of MPI-S is to notice key features of the skill as demonstrated by the mentor and ascertain the overall sense of the outcome. Students will learn how to reach the outcome in later steps of the teaching strategy.

9.1.2 Emulation

It is during this second step when the shift from teacher-led to student-led activities begin. The emulation step is related to the SRL phase of forethought (Fig. 9.2), like modeling, but is different because it guides students to set their own goals for NOS learning. During emulation, the role of the student is to replicate the scientific thinking and skills from the teacher model given a similar task as the model. However, the student is not expected to do this without support, and the teacher provides the students with a checklist to focus attention on an NOS aspect in the investigation. For example, when helping students to figure out what evidence they need and might be able to gather, students are supported in making observations with a checklist of the following statements:

- My observations describe what I see, hear, or touch.
- My observations are made up of measurements that other people can agree upon. For example, instead of saying “It is big,” I say “The blue car is 20 cm long.”
- My observations are clear so that other people who are not performing this lab could do exactly the same thing.
- My observations are clear enough so they can be used later to make conclusions.

Students use these statements to make their observations more empirical and less interpretative. Like cognitive apprenticeships, MPI-S helps students who may not have had prior access to ways of knowing in science. In later lessons, teachers can use different checklists for different aspects of NOS.

9.1.3 Self-Control

The self-control step of MPI-S is related to the performance phase of SRL (Fig. 9.2) because it helps students monitor their performance in learning an aspect of NOS. Students engaged in MPI-S to this point have observed what they are supposed to be accomplishing through the model (Modeling) and have attempted similar skills and knowledge with support from the teacher (Emulation). In the third step, the teacher continues to support student self-regulation of NOS learning but reduces support to allow students to actively reflect on their metacognitive strategies. Teachers should provide students with a more difficult attempt at the skill they are trying to build and give students only a few basic standards from which to check. Students are expected to take over more responsibility for learning and the teacher acts as the facilitator by providing basic support, only intervening when misconceptions arise. Using the NOS aspect of "evidence is required," teachers support students by providing the following shortened checklist during their inquiry investigation:

- My observations are clear to other people who are not performing this lab.
- My observations come only from my five senses, and are not inferences.
- My observations can be used later to make conclusions.

To check for appropriate metacognition in this step, teachers should ask a few questions about the choices that students make when they perform the skill such as

- How do you know something is true?
- Is your observation clear to other people? How do you know?
- What evidence do you have to support your idea? Is it directly connected?

If a student responds that something is true because they heard it from their parents, the teacher can move back into the emulation step and give more support to the student. When students can answer these questions in a way that is appropriate for scientists, then teachers can fade all support in the next step, self-reflection.

9.1.4 Self-Reflection

In the self-reflection step of MPI-S, students perform the targeted practice entirely on their own and reflect on the outcome. This last step of MPI-S is aligned to the self-reflection processes of SRL (Fig. 9.2) and build upon the self-control step because students are expected to regulate their learning without any support. Students should be able to demonstrate they can both understand and implement the NOS objective without any teacher support. In this step, the teacher gives the inquiry task and ensures that the student was able to accomplish it in a way that parallels scientific thinking. For example, a student may demonstrate her understanding of tentativeness in science by describing how new evidence has changed her conceptual model for a scientific phenomenon and how this is parallel to the way scientists decide on the strength of competing theories. Students provide evidence of their understanding of NOS by accomplishing the scientific task and by rationalizing their actions. The teacher can decide if the student has mastered the NOS aspect by evaluating student answers to the rationale. Prompts that a teacher would use regarding empiricism are:

- Explain how other people understand your observation out of context.
- Explain how your observations are detailed enough to be replicable.
- Explain how your observations are relevant to the purpose of the investigation.

Prompts for other elements of NOS have been developed and tested, and can be found in Table 9.1 (Peters 2012). Students who participated in MPI-S were able to answer these questions in a way that was scientific, and most notably, went back to the evidence when they had disputes within their group to the reason why a natural phenomenon happened. Students who did the same inquiry investigations but did not participate in the MPI-S often asked the teacher to tell them what the “right” answer was when faced with divergent conclusions for the evidence (Peters and Kitsantas 2010a; Peters 2012).

9.2 Sample Lessons

To demonstrate how the teaching strategy works, let’s consider the following guided inquiry lessons with embedded metacognitive prompts. Each lesson will feature one science content area and focus on one of the aspects of NOS. In the first lesson, students participate in an inquiry-based lesson on the gas laws and reflect on empiricism as an NOS aspect, while in the second lesson, students participate in an inquiry lesson on the science of atomic theory and the NOS aspects of tentativeness, durability, and the self-correcting nature of the scientific enterprise.

9.2.1 Inquiry Lesson on Gas Laws with Empiricism as an NOS Instructional Goal

This sample inquiry-based lesson on gas laws is intended for high school students and is planned for three block classes of 1.5 h each. At the conclusion of the lesson, students will be able to identify the properties of gases, know how to accurately measure each property, determine the relationships among pairs of the variables (e.g., temperature and pressure) through personal investigation, and to predict gas behavior based on the gas laws that they derive as part of this lesson. The NOS objective for this lesson is that evidence is required in science. Of course, this lesson could be adapted to focus on other NOS attributes such as shared methods (observa-

Table 9.1 Suite of metacognitive prompts for selected NOS elements

Steps of metacognitive prompts	Prompts
NOS element: Science is distinct from technology and engineering	
Step 1: Observation	Science and technology are used together when testing different materials to see if they conduct electricity, but they are distinct ideas. A circuit is built with a space to insert different materials. If the light bulb in the circuit lights up, then that material conducts electricity. If the light bulb in the circuit does not light up when a type of material is inserted, that type of material does not conduct electricity. The circuit and materials are technology, but the idea of electricity moving around the circuit and changing from electricity to light is science. Technology helps us to think of scientific ideas and scientific ideas help us to improve technological tools.
Step 2: Emulation	I made measurements that are based on a standard system like the metric system. I thought how I could use the measurement tools most accurately in this lab. I did not use measurements that were based on non-standardized tools, like my hand or height. I thought about many different tools that could have been used in this lab and chose the most useful one. I thought about how my measuring tool can interrupt what I am trying to measure. I thought about how people in history had different tools to measure and how these different tools could produce different results compared to my results.
Step 3: Self-control	I made measurements that are based on a standard system like the metric system. I thought about many different tools that could have been used in this lab and chose the most useful one. Would other people understand your measurement method? Could other tools be used to perform the measurement? How might that tool be more or less useful? Does your measurement method have a standard to against which to compare?
Step 4: Self-reflection	Does your measurement method have a standard to compare against? How does your measurement interrupt the phenomena you are measuring? What technologies are available to better describe the phenomena? What degree of accuracy can your measurement method offer?
NOS element: Tentative, durable, and self-correcting	
Step 1: Observation	William Gilbert in the 1700s noticed that a piece of iron on top of St. Augustine's chapel was magnetic. Gilbert thought that the metal became magnetic because of the winds. In the 1900s it was found that the piece of metal was magnetic because it was struck by lightning. The lightning magnetized the iron. Ideas in science are usually long-lasting but can sometimes change when new information is introduced.

(continued)

Table 9.1 (continued)

Steps of metacognitive prompts	Prompts
Step 2: Emulation	I know how scientists throughout history thought about this idea. I can see how this idea has changed when scientists got more information about it. I know that ideas in science change scientists agree the old idea doesn't fit with new information that is reliable. I know that scientists are strict about how they get information, so ideas in science are long-lasting.
Step 3: Self-control	I know that ideas in science change scientists agree the old idea doesn't fit with new information that is reliable. I know that scientists are strict about how they get information, so ideas in science are long-lasting. How has this lab changed the way you think about the phenomena? Was there a point in the lab where you were surprised about what happened? Explain the part of your lab that made you surprised and why you thought it was unusual.
Step 4: Self-reflection	What did people long ago think about the phenomena you were studying? How did people's ideas change over time about the topic for your lab? How can scientific knowledge be believed if it keeps changing over time?

tion, inference, induction, deduction, lack of a stepwise scientific method, distinction between laws and theories, and subjectivity). Planning lessons on the topics of gas laws are a good fit for the Metacognitive Prompting Intervention because the lessons give students multiple chances to explore solving similar problems (property of gases) leading to the synthesis of the relationships among pressure, volume, and temperature (gas laws). Each time students engage with a concept, they can also engage with the next developmental step of the metacognitive prompts.

9.2.1.1 Modeling

The first step for using MPI-S is for the expert (the teacher) to model the NOS concept of empiricism for students, noting the key features of the ways experts think and behave with respect to evidence and the need for evidence. Recall that this step in MPI-S is called modeling in the psychology sense of the word, so that the teacher demonstrates the expected learning outcome for students. For the gas laws, the teacher can begin by discussing the need to measure properties of gases in a way that allows others to understand the measurement system used. In other words, a standardized system of measurement is necessary for empiricism to be communicated accurately in the scientific community.

The teacher can begin by asking what types of variables can be measured for a mylar balloon. The teacher can guide the class discussion to be sure the key properties that can be measured about gases are accounted for: pressure, volume, amount, and temperature. Then, small groups of students should explore the system of measurement for each variable; this is not always an easy task with gases. For example, the property of volume requires some clever thinking about how to measure what is inside a balloon which is a large, non-uniform three-dimensional shape that compresses if you hold it too tightly. When considering how to measure pressure, students will need some kind of technology. Students assigned to explain "amount of gas" should address the conceptual idea of a mole, since they will not be able to directly measure the gas. Temperature has a measurement system that is straightforward and typically well known, but actually placing a thermometer or probe in the container for the gas may disrupt the system, so students must arrange for the system to remain stable while taking a measurement. Once the groups come to consensus about the way to measure the relevant variables of the gas in a balloon, they share it with the whole class and gain feedback to refine the measurement system. The teacher models the key features of empiricism by focusing students' attention on the ways they can measure most accurately and communicate this way of measuring to other students. The teacher should also extend students' thinking by asking students to use the system of measuring gas properties for other situations with gases, such as a hot air balloon, air in the classroom, or an airbag in a car.

9.2.1.2 Emulation

This step in MPI-S is called emulation because students are expected to follow the model that the teacher demonstrates. Since students are novices in learning about the NOS aspect, they will need some help. The teacher supports student engagement in another setting that illustrates the targeted NOS aspect by providing the students with a checklist to compare their thinking about the role of empiricism when learning about the relationships among the properties of gases. For this lesson, students empirically investigate the relationship of volume and temperature, and volume and amount of gas using a mylar balloon. The MPI-S checklist for this lesson is nine items long (see below), and emphasizes the view that (a) all concepts are knowable on the basis of experience, (b) beliefs or propositions are knowable only through the application of experience, and (c) words are meaningful because they convey concepts from experience (Peters and Kitsantas 2010a). Note that the prompt checklist has more items than features of empiricism listed above because the prompts are designed to give students multiple ways to check understanding of the same concept and to learn both NOS and traditional science content. The checklist for the emulation step is as follows:

- I am accurately measuring each variable in my investigation based on our group's decision on how to measure temperature, volume, and amount of gas.
- My observations and my classmates' observations align.
- I have a clear way of communicating the measurement of the variables so that others can understand what I have measured.
- I have translated my data into evidence without influence from my previous beliefs about the topic.

- I am regarding the evidence from each variable when explaining the relationships between variables (through inductive reasoning).
- I am not influenced by my previous beliefs about the variables, even if the evidence is different from my prior beliefs.
- I am providing enough detail in my procedure, results, and conclusion section of the report for others to replicate my work.
- People can do exactly the same investigation I performed based on what I have written.
- Someone who has not done this investigation could understand how I came to my conclusions based on my writing.

9.2.1.3 Self-Control

In this step, students perform more investigations on other properties of gases, led by questions such as what is the relationship between pressure and volume and what is the relationship between pressure and temperature, so that they gain more experience in their use of empiricism to make conclusions. Teachers hand off the control of the performance to students by reducing the number of checklist items as support and asking questions about students' justification of their conclusions. If students are becoming more self-regulated in their learning, they come to understand that they must collect data to justify conclusions in their investigation with less teacher support and will be able to articulate answers to the questions. If students are not progressing, then the teacher can continue to model empirically based thinking and give students the expanded checklist from the emulation step until students become more familiar the NOS aspect. Note that the checklist has been shortened to one bullet point representing each key element of empiricism.

- I am ensuring accuracy by measuring each variable in my investigation based on our group's decision on how to measure temperature, volume, and pressure of gas.
- I am not influenced by my previous beliefs about the variables, even if the evidence is different from my prior beliefs.
- What were your prior beliefs? Is your evidence different from or the same as what you initially understood?
- I am providing enough detail in my procedure, results and conclusion for others to replicate my work.
- What are your standards for "enough detail" from the bullet point above?

9.2.1.4 Self-Reflection

In the self-reflection step, students are expected to demonstrate they can explain the NOS element in their work without any support from the teacher. In the self-reflection step for this example lesson, students are asked to synthesize the relationships they found among pressure, volume, and temperature. Students employ the NOS concept independently and explain how they have related this NOS concept to the gas laws. Students use inductive reasoning to synthesize the results of the prior four investigations of pairs of variables for a complete statement. Students will also have to check the accuracy of the synthesized model with the evidence they collected in prior investigations.

In this step, students are expected to work independently, so there is no checklist, only questions asking them to articulate their choices.

- How do you know that your synthesized model of gases is accurate?
- Explain how your prior evidence can be used to explain the synthesized model of gases.

Once students can answer these questions in a way that is aligned with the scientific discipline, then they have the skills to be independent learners.

9.2.2 An Inquiry Lesson on the Development of the Atomic Theory with an Application on the Modern Periodic Table and the NOS Elements of Tentativeness, Durability, and Self-Correcting Nature of the Scientific Enterprise

This lesson is intended for high school students and consists of five teaching blocks of 1.5 h each. The first two blocks are focused on modeling and emulation. Students are engaged in self-control for the third block. Self-reflection is emphasized in the remaining two blocks. The content objectives for this lesson are for the student to accurately describe the Bohr atomic model and Schrodinger's atomic model and explain the implications of each model on reactivity of elements. The targeted NOS objective is to describe how the nature of scientific knowledge (tentative, durable, and self-correcting) led to the development of the modern atomic theory. The historical progress of knowledge in this lesson provides multiple opportunities where MPI-S can be used to focus students on the nature of scientific knowledge. Much like the gas laws lesson, each block in the lesson is designed for students to move to the next developmental level of the metacognitive prompts. Additionally, MPI-S used in this lesson could be adapted across multiple lessons as students explore the development of new scientific knowledge (e.g., development of evolutionary theory).

9.2.2.1 Modeling

As students explore the development of the atomic model, it is helpful to start by examining Democritus' model. The teacher leads a conversation on how Democritus' might have theoretically described that atoms might exist, but that it had little scientific evidence to support the model. It is important that students are made aware of the thought processes used by Democritus to theoretically describe that atoms exist. Additionally, the teacher should help the students recognize the difference between a claim and evidence in a scientific argument. As students and the teacher reexamine Democritus' claims, it should be recognized that little scientific evidence was provided to support the model. Discussions with students should explore or reinforce what constitutes scientific evidence, focusing on data collected using a systematic approach. Additionally, students and the teacher should examine how multiple lines of supporting scientific evidence would increase our confidence that a claim is valid. Students then are asked to conduct various chemical investigations that help them identify patterns, test them under new conditions, and explore what is already known to "discover" the three laws Dalton used to generate his atomic theory (law of conservation of mass, law of definite proportions, and law of multiple proportions). The teacher conducts a discussion with the students how Dalton's theory and the associated laws would constitute an example of the use of evidence in developing scientific knowledge. In addition, the teacher discusses with the students that scientific knowledge should also have explanatory or predictive power. The greater the number of settings in which the knowledge can be used (multiple lines of evidence), the more durable the knowledge becomes.

Students are then asked to conduct an inquiry investigation exploring Thomson's work with cathode rays using a simulation (for instruction, see the Concord Consortium—Crookes Tube; https://concord.org/). Once the investigation is complete, the teacher leads a discussion with students focusing their results (Thomson's discovery of the electron) on the refutation of Dalton's tenet that atoms are the smallest particles of matter. Further discussion examines other aspects of Dalton's atomic theory to determine that the evidence does not impact the overall understanding of how the atom might function in chemical reactions, but does provide a revised view of atomic structure. The teacher should focus the students on the fact that through the scientific process, Dalton's model was modified, not discarded thus making an important point about durability and self-correction.

9.2.2.2 Emulation

Students are then be introduced to Thomson's plum pudding model and Nagaoka's Saturnian model of atomic structure. They will be asked to use the following checklist to determine if the model is scientific and durable:

- The model is based on scientific evidence collected in a systematic way.
- The evidence used inspires confidence in the conclusions because it includes many trials and multiple lines of evidence.
- The model can be used to predict or explain outcomes in multiple settings.

Students will likely find that both models meet the criteria which make them scientific, but the durability is weaker as each model has limited lines of reasoning and predictive/explanatory power.

Students are then asked to conduct an inquiry investigation where they simulate the Marsden–Rutherford gold foil experiment (see the King's Centre for Visualization in Science—Rutherford Experiment; http://www.kcvs.ca/site/index.html). Once they have completed the simulation, students would then be asked to use the following checklist regarding the tentativeness to reexamine the Thomson and Nagaoka models.

- The new evidence completely contradicts a critical component of the model, resulting in questioning the validity of the entire model.
- The new evidence contradicts a non-critical component of the model, but other parts are unaffected and remain valid.
- New evidence provides more detail of the model not previously understood, resulting in the revised model becoming more explanatory/predictive.

Students should determine that their evidence results in questioning the validity of Thomson's entire model and should therefore be refuted. However, Nagaoka's model would have been supported and would only need to be revised to include a small, positively charged nucleus. The instructor could then discuss the remaining evidence from Chadwick's efforts at discovering and describing neutrons that further elaborated on the atomic model.

9.2.2.3 Self-Control

Students would then be asked to investigate the development of the periodic table by first conducting a classification of the elements similar to how Mendeleev approached the same challenge (Nargund and Park Rogers 2009). They will then examine the work of Mendeleev and Moseley in more depth using a Web Quest. They will be asked to describe the contributions of each scientist then focus on the following questions:

- What did they do to determine if Mendeleev and Moseley's work scientific?
- What did they do to determine if the knowledge Mendeleev and Moseley generated was durable?
- What did they do to evaluate the tentativeness of Mendeleev and Moseley work?

9.2.2.4 Self-Reflection

Students complete their exploration of the atomic model by investigating a model of the hydrogen atom using a computer simulation comparing multiple atomic models (PhET Interactive Simulations—Models of the Hydrogen Atom; phet.colorado.edu). Students will first be introduced to simulation and focused on the different models and their prediction. Students will need to do some exploration of each model to understand why the simulation is behaving as it is. In particular, they would need to understand the orbital structure of Bohr's and Nagaoka's model as well as Schrodinger's electron cloud. They would then proceed to test each of the model's to determine which show promise to explain the behavior of the simulation. They would then explore a second simulation to focus on a comparison of the Bohr and Schodinger models (see the Concord Consortium—Atomic Structure; concord.org). During each of the simulations, students have to decide which models appear valid and describe their choices by focusing on the following questions:

- Why did you decide the model was scientific knowledge?
- Why did you think the models you selected were durable?
- Why would these models be tentative?

9.3 Creating Metacognitive Prompts of NOS for Other Lessons

In this section, we discuss how teachers can create a suite of metacognitive prompts for their own lessons and how to place them within the lesson to support student self-regulation of NOS learning. Educators can create metacognitive prompts aligned to SRL by changing the learning task, while keeping the theoretical structure of the MPI-S teaching strategy. SRL has been shown to be effective in supporting learners to be independent in many different contexts such as instructional media (Henderson 1986), volleyball skills (Zimmerman and Kitsantas 1997), science instruction (Cleary and Labuhn 2013), scientific thinking (Peters and Kitsantas 2010a; Peters 2012), teaching using inquiry (Peters-Burton and Botov 2017), and teaching using argumentation (Peters-Burton 2013). The following guide will help instructors to construct metacognitive prompts for their needs.

9.3.1 Format for Metacognitive Prompts

The first step in constructing metacognitive prompts is to consider and compile what students are expected to know and do for the NOS learning task. For example, in order to teach the concept "evidence is necessary," instructors should research what makes data empirical and compose a list of characteristics of empirical data. If another NOS aspect is chosen, then the checklist items would be different (see Table 9.1). The modeling step teacher demonstration and the emulation step checklists for students are generated from this list of characteristics. The teacher demonstrates the characteristics of the NOS aspect during the modeling step in the context of the inquiry-based lesson. For example, when modeling how to make observations, the teacher models appropriate examples by explicitly describing the reason behind their actions (having a shared understanding of the measurements and providing enough detail to be replicated) as well as non-examples (making judgments such as "big and small" which can be discussed as erroneous). Once the identified characteristics are demonstrated by the teacher, possibly in written form as the class analyzes a set of written observations, the instructor should create checklist points for all characteristics of the NOS aspect in the emulation step. Teachers should write the same characteristics of the targeted NOS objective in two or more ways for the first set of checklist points to give students several chances to address the characteristic. To create prompts and questions for the self-control step, the instructor should pare down the emulation step checklist to a few core characteristics of the NOS aspect. In addition to the shortened list, the instructor should also compose a few questions asking students to verify the choices they are making related to the NOS objective. For the final self-reflection step, instructors should create questions regarding the rationale for the core characteristics are created. In other words, in the final step, students should be able to justify how their choices are aligned with the NOS objective, that is, how they are acting and thinking like scientists.

9.3.2 Embedding the Suite of Prompts into Inquiry Instruction

In order to use the four sets of prompts (one prompt set of checklists and/or questions for each step), the instructor must design activities that engage students in the targeted NOS aspects multiple times. The prompts (checklists and/or questions) can be used multiple times over the course of a unit, but must be used at least once in the order of the developmental steps: observation, emulation, self-control, and self-reflection. All four steps of prompts do not need to be present in one lesson. Rather, students' metacognition, or awareness about their understanding, about NOS aspects should be built over time, giving students the opportunity to try, fail, try again, and succeed. The MPI-S strategies are designed to be employed over similar tasks, and similar tasks may not occur within one lesson. For example, if students are learning about "the tentative, durable, and self-correcting" aspects of science, this may occur across four different investigations, each with a different context but with the same focus on the NOS aspects. Doing this has the advantage of allowing students to see that NOS functions across science disciplines. Teachers can embed the modeling step in the first inquiry dealing with "the tentative, durable, and self-correcting" NOS aspect, the emulation step in the second inquiry dealing with tentativeness, the self-control step in the third inquiry dealing with tentativeness, and the self-reflection step in the fourth inquiry dealing with tentativeness.

The instructor should be cognizant of the appropriate use of the prompts by students, which is often easier to assess in the later prompts that include questions. To assess the checklists, the instructor can observe students engaging in the targeted NOS objective, and to assess the questions, the instructors can assess the answers to the questions for the appropriate use of the key characteristics developed in the formatting process. For example, when assessing checklists for "evidence is required" the instructor can look for an individual student's respect for evidence (successful use of prompt) when engaged in inquiry or student naïve adherence to prior beliefs that are not aligned with evidence (unsuccessful use of prompt). Alignment to the NOS objective may be more directly assessed with the question portions of the prompts because students are answering direct questions about their scientific activities.

9.4 Summary

Metacognitive prompts are a flexible instructional tool because they can be embedded into any content area to help students to focus on the ways they engage in science explicitly and reflectively (Peters 2012; Peters and Kitsantas 2010a). The prompts can be designed for all NOS aspects, no matter the model, and can be applied in any traditional science content area. Not only can the metacognitive prompts be used for any learning tasks regarding both content and NOS aspects, but as standards change, the prompts can be adapted to help students focus on the objectives. As long as a clear objective for content learning and a clear objective for NOS learning are identified, metacognitive prompts can be used in a variety of learning settings.

Metacognitive prompts also give students more confidence in science classes. Often students feel that they are left out of science because they are not aware of the underpinning traditions and behaviors that may be apparent to scientists and science educators, but are unspoken and therefore out of reach for those not yet engaged in science. Metacognitive prompts articulate the ways that the discipline of science operates but is not directly communicated. Students who have used MPI-S have explained their views of science have changed because of the prompts and have said that they knew that doing science was different than other subjects, but they didn't know how until they used the prompts (Peters and Kitsantas 2010a). The prompts can be used as an instructional tool via describing the ways scientists think and act, but they can also be simultaneously an assessment tool that gauges the level of proficiency or sophistication a student has in a particular NOS aspect. Assessment of NOS aspects is notoriously difficult because they are epistemic understandings and students may not even be aware that they hold these beliefs. However, metacognitive prompts get this tacit knowledge into the open for discussion and clarification.

Finally, metacognitive prompts build on prior work in the field of nature of science education by giving structure to explicit, reflective instructional approaches that have had some recent success in improving learners' views of NOS. Metacognitive prompts change explicit, reflective instruction into a teaching strategy, thus giving it structure and intentionality, backed by SRL that has had many years of empirical support. Metacognitive prompts also expand on the work of science educators by setting up a structure where students must make attempts at demonstrating their understanding of the NOS aspect multiple times, thus giving students more time to form an understanding of the same NOS aspect from different perspectives. Metacognitive prompts have the extended power of being supported by science education research and educational psychology, therefore bringing the necessity of evidence full circle into science classrooms.

References

Butler, D. L., Beckingham, B., & Lauscher, H. J. N. (2005). Promoting strategic learning by eighth-grade students struggling in mathematics: A report of three case studies. *Learning Disabilities Research and Practice, 20*, 156–174.

Cleary, T. J., & Labuhn, A. (2013). Application of cyclical self-regulation interventions in science-based contexts. In H. Bembenutty, T. J. Cleary, & A. Kitasantas (Eds.), *Applications of self-regulated learning across diverse disciplines: A tribute to Barry J. Zimmerman* (pp. 89–124). Charlotte: Information Age Publishing.

Cleary, T. J., & Platten, P. (2013). Examining the correspondence between self-regulated learning and academic achievement: A case study analysis [Special Issue]. *Educational Research International*, *2013*.

Collins, A., Brown, J. S., & Newman, S. E. (1987). *Cognitive apprenticeship: Teaching the craft of reading, writing and mathematics* (Technical report no. 403). Cambridge, MA: BBN Laboratories. Centre for the Study of Reading, University of Illinois.

De Corte, E., Mason, L., Depaepe, F., & Verschaffel, L. (2011). Self-regulation of mathematical knowledge and skills. In B. J. Zimmerman & D. H. Schunk (Eds.), *Handbook of self-regulation of learning and performance* (pp. 155–172). New York: Routledge.

Driscoll, M. P. (2000). *Psychology of learning for instruction*. Boston: Allyn & Bacon.

Duschl, R. (1990). *Restructuring science education: The role of theories and their importance*. New York: Teachers College Press.

Graham, S., & Harris, H. R. (2005). Improving the writing performance of young struggling writers: Theoretical and programmatic research from the center on accelerating student learning. *The Journal of Special Education, 39*, 19–33.

Guthrie, J. T., & Wigfield, A. (2000). Engagement and motivation in reading. In M. L. Kamil, P. B. Mosenthal, P. D. Pearson, & R. Barr (Eds.), *Handbook of reading research* (3rd ed., pp. 403–422). New York: Longman.

Henderson, R. W. (1986). Self-regulated learning: Implications for the design of instructional media. *Contemporary Educational Psychology, 11*, 405–427.

Hofer, B. K., & Pintrich, P. R. (1997). The development of epistemological theories: Beliefs about knowledge and knowing and their relation to learning. *Review of Educational Research, 67*, 88–140.

Hogan, K. (2000). Exploring a process view of students' knowledge about the nature of science. *Science Education, 84*, 51–70.

Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth graders' views of nature of science. *Journal of Research in Science Teaching, 39*, 551–578.

King, P. M., & Kitchener, K. S. (1994). *Developing reflective judgment: Understanding and promoting intellectual growth and critical thinking in adolescents and adults*. San Francisco: Jossey-Bass.

Nargund, V., & Park Rogers, M. A. (2009). That is not where that element goes…ah, the nature of science. *Science Scope, 10*, 23–29.

Peters, E. E. (2009). *Thinking like scientists: Using metacognitive prompts to develop nature of science knowledge*. Saarbrücken: Verlag Dr. Müller Aktiengesellschaft & Co. KG Publishers.

Peters, E. E. (2012). Developing content knowledge in students through explicit teaching of the nature of science: Influences of goal setting and self-monitoring. *Science & Education, 21*(6), 881–898. https://doi.org/10.1007/s11191-009-9219-1.

Peters, E. E., & Kitsantas, A. (2010a). Self-regulation of student epistemic thinking in science: The role of metacognitive prompts. *Educational Psychology, 30*(1), 27–52. https://doi.org/10.1080/01443410903353294.

Peters, E. E., & Kitsantas, A. (2010b). The effect of nature of science metacognitive prompts on science students' content and nature of science knowledge, metacognition, and self-regulatory efficacy. *School Science and Mathematics, 110*, 382–396. https://doi.org/10.1111/j.1949-8594.2010.00050.x.

Peters-Burton, E. E. (2013). The use of clinical interviews to develop in-service secondary science teachers' nature of science knowledge and assessment of student NOS knowledge. *The Clearing House: A Journal of Educational Strategies, Issues and Ideas, 86*(6), 229–237.

Peters-Burton, E. E. (2015). Outcomes of a self-regulatory curriculum model: Network analysis of middle school students' views of nature of science. *Science & Education, 24*, 855–885. https://doi.org/10.1007/s11191-015-9769-3.

Peters-Burton, E. E. (2017). Strategies for learning nature of science knowledge: A perspective from educational psychology. In M. R. Matthews (Ed.), *History, philosophy and science teaching: New perspectives* (pp. 167–193). Dordrecht: Springer.

Peters-Burton, E. E., & Botov, I. S. (2017). Self-regulated learning microanalysis as a tool to inform professional development delivery in real-time. *Metacognition and Learning, 12*(1), 45–78. https://doi.org/10.1007/s11409-016-9160-z.

Sinatra, G. M., & Taasoobshirazi, G. (2011). Intentional conceptual change: The self-regulation of science. In B. J. Zimmerman, B. J, & D. H. Schunk (Eds.), *Handbook of self-regulation of learning and performance* (pp. 203–216). New York: Routledge.

Zimmerman, B. J. (2000). Attaining self-regulation: A social-cognitive perspective. In M. Boekaerts, P. Pintrich, & M. Zeidner (Eds.), *Handbook of self-regulation* (pp. 13–39). San Diego: Academic Press.

Zimmerman, B. J. (2008). Investigating self-regulation and motivation: Historical background, methodological developments, and future prospects. *American Education Research Journal, 45*, 166–183.

Zimmerman, B. J., & Kitsantas, A. (1997). Developmental phases in self-regulation: Shifting from process goals to outcome goals. *Journal of Educational Psychology, 89*, 29–36.

Chapter 10
Teaching Nature of Science Through a Critical Thinking Approach

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10.1 Introduction

In this volume, McComas suggests a number of nature of science (NOS)-related ideas called *subdomains* for the inclusion of NOS in school science. Previously he (e.g., McComas 1998, 2004) and others (e.g., Lederman 2004; Osborne et al. 2003) have developed groups of NOS-related ideas that should be the focus of instruction in K-12 science classrooms. These NOS-related ideas constitute the substantive content of NOS to be taught to students and have received positive reviews by many science educators (e.g., Akerson et al. 2000; Akerson et al. 2011; Khishfe 2008; Khishfe and Abd-El-Khalick 2002; Kim and Irving 2010; Paraskevopoulou and Koliopoulos 2011; Yacoubian and BouJaoude 2010). These and other educators have developed studies in which they have used similar NOS-related ideas and have aimed at guiding students to develop their NOS understandings through engaging them in explicit and reflective discussions on NOS.

In my opinion, *critical thinking* (CT) needs to be a foundational pillar of NOS in school science (Yacoubian 2015). In this chapter, I discuss why and how NOS should be taught *critically* at schools. In taking such a position, I do not underestimate the value of explicit and reflective discussions. As referenced earlier, such discussions have been found to be quite effective. In the paragraphs that follow, I propose CT as a framework for addressing NOS in school science. Such a proposal does not contradict with the method of explicit reflective discussions. In fact, it provides a direction for those discussions.

There are a number of reasons for addressing NOS in school science. Among these reasons are humanizing of the sciences and situating them in personal, ethical, cultural, and political contexts and promoting critical thinking (Matthews 1994).

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_10

These are in addition to enhancing decision making (McComas 1998), particularly on socioscientific issues (Kolstø 2001a; Zeidler et al. 2002), which are controversial social issues related to science with no clear-cut solutions (Sadler 2011). CT is “reasonable reflective thinking focused on deciding what to believe or do” (Ennis 2018a, p. 166). It includes a set of knowledge (e.g., concepts), abilities, and dispositions (Ennis 1996a, b, 2018a; Hitchcock 2018). It is considered an important aspect of scientific literacy (Gunn et al. 2007).

10.2 NOS and Critical Thinking (CT)

There are a number of good reasons for why students need to develop their NOS understandings critically. ***First, CT is a “fundamental educational ideal” (Siegel 1988, p. 2) and almost no one would disagree that it has an important role in the science curriculum.*** There is no reason for why it should not also have a foundational presence in the teaching and learning of NOS (of course, assuming here that one understands the importance of NOS in school science to start with). Siegel explores four main considerations to justify CT as an educational ideal: (1) a moral obligation to respect students as persons, (2) preparation of students for the successful management of adult life, (3) the need of initiation into the rational traditions, and (4) preparing democratic citizens.

Second, CT as a framework for addressing NOS in school science has the potential to help students make good decisions about what views of NOS to adopt. CT is fundamental to decision making (Ennis 1989, 1996a; Lipman 2003; Siegel 1988) and future citizens need to be guided to practice making decisions in the context of NOS. Engaging students in explicit and reflective discussions on NOS-related ideas facilitates in-depth exploration of those ideas to some degree. However, when students start exploring those ideas at depth, they will at some point face divergent and competing positions and thus will need to make decisions regarding those positions—mimicking the skills used by professionals involved in philosophical debates.

One might argue that at the precollege level students rarely engage in decision making on NOS views. After all the aim of K-12 science education is not to prepare philosophers of science. I agree. However, I also approach this issue from a different angle and believe decision making on NOS views can be and should be done in developmentally appropriate ways that progresses as one moves from elementary to secondary and then to the college level. Almost everything taught at schools can be and should be situated across a learning trajectory that provides experiences conducive to their in-depth exploration. Otherwise, learning becomes no more than memorizing facts. Learning NOS should not be an exception to this.

Accordingly, the NOS-related ideas proposed by McComas need to be treated as broad ideas that can have the potential to engage students in some in-depth explorations about them. Abd-El-Khalick (2012a) has suggested that it is important to keep the focus on NOS-related ideas while ensuring that these ideas are “addressed at increasing levels of depth as students move along the educational ladder from elementary school to college-level science teacher education programs" (p. 1047). The NOS-related ideas need to have curricular scope and sequence that get addressed in developmentally appropriate ways and in more depth at every level—whether at the elementary, middle, secondary, or the college level; otherwise, we might risk falling into the trap of treating them as no more than definitions. The latter would encourage rote memorization where students might be at risk of repeatedly learning the same ideas instead of digging deeper into them across a well-defined learning trajectory.

In case of NOS learning, going in depth would also involve making decisions regarding NOS views. This is because of the contested nature of the content that NOS entails. Engaging students in NOS learning at increasing levels of depth would eventually involve having them explore controversies and take critical stance—or at least having them *practice* to do so in developmentally appropriate ways as far as school science is concerned. Consequently, students would need to develop a *critical mindset* as they develop their NOS understandings.

It might look like some of the NOS-related ideas proposed by McComas are easier to teach than others, yet challenges arise as one enters into the details. To elaborate, consider the NOS-related idea that *science is tentative, durable, and self-correcting*. An in-depth exploration, as illustrated in the section that follows, would entail, at some stage across the learning trajectory, students wondering and raising questions as what is tentativeness? How is science tentative? How can scientific knowledge be tentative yet at the same time durable? At a more advanced stage they may need to start exploring different views on tentativeness in science and would also start thinking about, say, whether to adopt a realist or an instrumentalist position for tentativeness in science. The intention here is not to enter into discussions on what students can and cannot do at every developmental level, as that would be an empirical question to pursue. The point that I am trying to make is that students would need to engage in CT to adopt certain positions as they explore those and similar questions. Consequently, throughout their NOS learning pathway, students need to develop a critical mindset, even if as novices they will not make full-fledged decisions on NOS views or adopt positions. A critical mindset would enable them to start developing some CT-related abilities and dispositions, within the context of NOS, so that they can more reasonably explore and appreciate those controversies at more advanced stages in their learning.

Consequently, CT as a framework for addressing NOS in school science has the potential to foster the development of learning experiences not only for an in-depth exploration of NOS but also for decision-making.

Third, CT as a framework for addressing NOS in school science provides the possibility of a developmental pathway for NOS learning using CT as a progression unit. The lack of a developmental pathway for NOS learning has been acknowledged by a few researchers (e.g., Abd-El-Khalick 2012a). Creating a pedagogical sequence for NOS in K-12 science education has been quite a challenge. Many science educators have targeted the same NOS-related ideas across different grade levels and teacher education programs. Combinations of similar NOS-related ideas are used to teach middle school students (e.g., Yacoubian and BouJaoude 2010), secondary students (Bell et al. 2003), preservice science teachers (Schwartz et al. 2004), and in-service science teachers (Akerson and Hanuscin 2007).

Arguably, one reason for the lack of studies that situate NOS instruction in an increasing level of depth can be related to the difficulty in determining what could count as "complex" and "specific" NOS understandings to use Abd-El-Khalick's (2012a) words. It would be hard to come to an agreement as to which philosophical view or views of NOS would be considered the desired "complex" and "specific" NOS understandings, unless a decision is made to move the spotlight away from the substantive content of NOS and focus on the CT process. CT as a foundational pillar of NOS in school science would necessitate developing a developmental pathway for school NOS using CT as a progression unit. One might think about a developmental pathway for NOS learning in terms of a student's engaging in CT about NOS. This seems a plausible path to take especially that there is already some evidence on the developmental nature of CT (e.g., Duschl et al. 2007; Keating 1988; King and Kitchener 1994; Kuhn 1999; Nicoll 1996).

Fourth, pedagogically speaking, the CT literature can provide resources to guide students as they explore NOS. CT has certain attributes the understandings and use of which can enable the critical thinker to produce reasonable decisions. There are several conceptions of CT (Hitchcock 2018). Ennis (2018a) considers that those conceptions are not significantly different from each other and that leads into deriving similar lists of abilities and dispositions from them.

Ennis's work (e.g., Ennis 1996a, 2018a) has involved the dissection of CT into abilities (e.g., judge the credibility of a source, analyze arguments) and dispositions (e.g., try to be well-informed, be alert for alternatives). Throughout his academic career, Ennis has refined his list to make it more rigorous and comprehensive. There is no need to list here those abilities and dispositions. His most updated list can be found in his recent publications (e.g., Ennis 2018a) as well as on a website developed by him and Sean F. Ennis, which can be accessed through the following link: http://criticalthinking.net/index.php/longdefinition/ (Ennis 2018b).

Based on a review of the literature of CT, Hitchcock (2018) differentiates between two kinds of dispositions, namely initiating dispositions (e.g., open-mindedness, trust in reason, seeking the truth) and internal dispositions (e.g., the disposition to formulate the issue clearly and to maintain focus on it). Hitchcock also describes a number of abilities (e.g., observational, questioning, inferential, and argument analysis abilities) and highlights the importance of *knowledge* of CT concepts, of CT principles, and of the subject matter of the thinking.

A teacher may borrow from lists of knowledge, abilities, and dispositions of CT such as those developed by Ennis, Hitchcock, or others and use them as resources while guiding students in a NOS lesson. Those lists can become a comprehensive frame of reference for both the teacher and the student and can act as a mediator for one to penetrate more deeply into one's thinking. Students can thus engage in deeper thinking about NOS when they are guided to practice some of those CT-related abilities and dispositions and to reflect on the underlying knowledge of CT concepts and principles—all within the context of NOS. Consequently, from a pedagogical perspective, those lists are appealing because they provide a practical starting place for teaching NOS critically. They have the potential (1) to foster a framework for the development of educational programs, standards, and resources and (2) to facilitate in-depth discussions about NOS.

Fifth, CT as a framework for addressing NOS would make the learning of NOS more authentic. When philosophers, sociologists, historians of science, and science educators engage in philosophical debates about NOS, CT about NOS is often at the foreground of their debates. They engage in making decisions about their views, about others' views, and about what to accept or not to accept. As a result, the NOS-related positions produced are quite divergent and competing.

The science education community is well aware of the undesired consequences of teaching scientific knowledge without regard for the *processes* by which that knowledge is produced. For instance, detaching scientific content knowledge from the processes promotes a naive view of the nature of scientific inquiry resulting in an image of science as a collection of isolated facts (Schwab 1962). As a remedy, the science education community reached a broad agreement on the importance and role of inquiry in the teaching and learning of science (e.g., Krajcik et al. 1998; NRC 1996; Roth 1995; Schwab 1962; Tamir 1983). Using the same logic, detaching the substantive NOS content from the process of its development promotes a naive view of philosophy of science: It portrays an image of NOS as a collection of isolated facts. It also promotes a nonauthentic image of the philosophical discourse on NOS and the process of how the substantive content of NOS develops.

CT as a framework for addressing NOS would bring CT into the foreground of school NOS, moving the substantive NOS content into the background. Rather than working towards developing adequate NOS understandings among students, the focus would be placed on the *process* as students would be guided to practice making judgments on NOS views, or at the minimal level develop a *mindset* so that they could eventually make informed judgments on NOS views.

As an example, a secondary student could be considered to have more authentic (and deeper) understandings of McComas's proposed NOS-related idea that "science is tentative, durable and self correcting" when she explores this idea *critically* compared to when she explores it non-critically, because critical exploration would entail learning not only about the NOS-related idea per se but also the *process* by which this NOS-related idea is explored in philosophical circles. Such a proposal makes the position of CT foundational: CT rather than the substantive NOS content gets situated in the foreground of school NOS, while NOS as a set of concepts/ideas moves from the foreground of NOS instruction into the background.

Having discussed five reasons for why students need to develop their NOS understandings critically, I now place the spotlight on *how* to teach NOS through the lens of CT.

10.3 Teaching NOS Critically

Based on the discussion in the previous section, I now outline a procedure that could be useful in teaching NOS critically. For illustration, let us suppose that students in a secondary classroom would be guided to investigate McComas's proposed NOS-related ideas that "science is tentative, durable and self correcting" and that "evidence is required in science".

First, establish the necessary platform on which critical exploration of NOS can take place. This can be done by creating a background context so that discussions about NOS revolve around concrete situations. Abd-El-Khalick (2012b) has identified several contexts that science education researchers have relied upon in designing NOS interventions. For the purpose of elaborating an example, the context chosen would be socioscientific issues through which students can explore certain NOS-related idea(s). Having well-reasoned views of NOS can also support citizens in making decisions on socioscientific issues (Driver et al. 1996; Kolstø 2001a; Yacoubian 2015; Zeidler et al. 2002). So it is a two-way process.

For example, evolutionary biology and electromagnetic radiation are two content topics covered in high school science curricula. These lend themselves to a number of socioscientific issues such as the following:

(1) Whether creationism should be taught in high school science classes
(2) Whether new houses should be built next to high-voltage power lines.

Both issues are controversial and relevant to the lives of students. Hence, they could create a good context for NOS discussions. Both could be targeted from a NOS perspective, as well as from political, policy, aesthetics, ethical, health, and other perspectives. A teacher should guide the students to explore these issues from multiple perspectives, given that various perspectives could be valuable and one may eventually make use of a combination of them in making judgments. Nonetheless, I delimit my discussion to the NOS perspective here. I also believe that a teacher cannot guide the students to develop in-depth understandings of all the perspectives simultaneously. There is always choice involved in terms of which perspective will be the focus of discussion at a specific time, despite the fact that there could be room for integration among different perspectives.

Second, provide a NOS focus to the lesson. It is important that the exploration of one or more NOS-related ideas becomes a targeted focus of the lesson. Let us assume that we decide to focus the discussion of the first issue on *creationism and the tentative aspect of science* and that of the second issue on the *relationship between long-term exposure of magnetic fields of the type generated by high-voltage power lines and cancer incidence of children*. Two focused questions can be generated:

(Q1) To what extent are creationists' views on the origin of life tentative?
(Q2) To what extent does evidence suggest a relation between exposure of magnetic fields of the type generated by high-voltage power lines and cancer incidence of children?

A student needs to use her understandings of NOS in order to engage in a meaningful discussion and answer Q1 and Q2. In particular, she needs to use her understandings of the terms "tentativeness" and "relation" respectively. In these situations, the student is being asked to use her NOS understandings to make judgments.

Third, develop a learning activity that can engage students in critical exploration of the NOS-related ideas in question. In order to appreciate the complexity of the issues, a student needs to be exposed to the different viewpoints concerned. For instance, the student could be guided to be exposed to contradictory philosophical positions on creationism and the tentative aspect of science as she thinks about Q1 and she may be exposed to contradictory scientific research findings on the relationship between long-term exposure of magnetic fields of the type generated by high-voltage power lines and cancer incidence of children as she thinks about Q2. I acknowledge that students at the precollege level are often not in a position of being able to read primary literature in philosophy and science. Exposing students to read secondary literature or adapted versions of primary literature (Yarden et al. 2001) might be ways of introducing the controversies. It is worth noting that the learning activity could also take other forms such as asking students to do some background research by themselves.

Fourth, engage students in critical exploration of NOS while facilitating explicit reflective discussions. When teachers engage their students in explicit reflective discussions on NOS, they consider the development of their students' NOS understandings as target cognitive instructional outcome. When students will be guided to explore NOS critically within the context of explicit reflective discussions, CT is the particular type of inquiry that students would need to engage in as they learn how to make decisions on NOS views. Hence, thinking critically about NOS would become a target instructional outcome.

As students engage in critical exploration of NOS, a teacher needs to explicitly target the development of CT-related knowledge, abilities, and dispositions among students. Teachers need to create opportunities where students could enhance their CT by understanding concepts and criteria of CT, developing the required abilities and the dispositions, as well as applying them in decision making (Abrami et al. 2008).

Considering our example, in order to be able to formulate her positions on Q1 and Q2, and in order to formulate them well, the student needs to be provided with opportunities to analyze and evaluate what the terms "tentativeness" and "relation" mean in these contexts and what significance they have. These are key terms around which philosophical discussion *about* NOS can happen. Specifically, reflecting on these terms can respectively help students develop deeper understandings about McComas's proposed NOS-related ideas that "science is tentative, durable and self correcting" and that "evidence is required in science" within the context of the chosen foci, socioscientific issues, and the content topics.

Consequently, in order for the student to be able to answer Q1 and Q2 and answer them well, she needs to think in the first place about more fundamental questions. These questions could be as follows:

(Q1a) How is science tentative?
(Q2a) In what circumstances could a causal inference between variables be considered a strong one?

Note that in Q1a the focus is being placed on developing understandings of tentativeness in science, whereas in Q2a the focus is on developing understandings of causal inference. Note how students practice making decisions: Through Q1a and Q2a they are encouraged to practice making judgments *about* NOS as there is no single view out there about tentativeness in science and what that means within the context of creationism. The debate between Ruse (1982) and Laudan (1982) is quite illustrative in that regard. Moreover, there is no clear-cut point in deciding when causal inference between variables can be considered strong. In fact, this also partly explains the availability of contradictory findings in the literature when it comes to Q2.

Accordingly, Q1a and Q2a are designed so that students can engage in a critical analysis of some of these interpretations and try to make judgments on them. As far as Q1a is concerned, once the students have given some thought about tentativeness in science, they can be guided to apply their understandings of tentativeness to evaluate the extent to which creationists' views on the origin of life could be subject to change and thus defend a position regarding Q1. This might require the student to analyze accounts of tentativeness in the context of the issue in question with the purpose of developing an understanding of the context, and then to apply her understanding of tentativeness to this context.

Concerning Q2a, research studies that explore a relationship between long-term exposure of magnetic fields of the type generated by high-voltage power lines and cancer incidence of children are usually epidemiological in nature, and many of them are designed as case–control studies. Experimental studies on humans are rare. Q2a is formulated so that students can be guided to develop understandings of causal generalizations. Once the students have given some thought to causal generalizations, they are in a better position to think about Q2. Here they are guided to use their understandings of causal relationships to evaluate the extent to which evidence supports a relationship between long-term exposure of magnetic fields of the type generated by high-voltage power lines and cancer incidence of children.

One or a combination of CT dispositions, abilities, and their underlying concepts discussed in the previous section could be targeted here. As students through Q1a and Q2a engage in critical exploration of some of the interpretations on tentativeness in science as well as causal generalizations, they can be guided to practice CT abilities such as *inferential* and *argument analysis* abilities (Ennis 2018a; Hitchcock 2018). As further teaching resources, a teacher, for instance, can make use of the detailed lists of criteria under each of these abilities developed by Ennis (2018b). Students can also be guided to reflect upon the underlying concepts of these abilities. Furthermore, they can internalize CT dispositions such as open-mindedness and being alert for alternatives (Ennis 2018a; Hitchcock 2018).

A final note: As previously stated, the aim of engaging students in such lessons is not to prepare them to become philosophers of science. Guiding students to practice making decisions on NOS views should be done in developmentally appropriate ways. Conducting such lessons would be feasible only if during earlier years of schooling, students are exposed to the necessary prerequisites on the learning trajectory. It is beyond the scope of this chapter to provide a full-fledged developmental pathway for NOS learning. Consulting the literature on developmental research can be helpful to identify certain elements helpful in designing a developmental trajectory for NOS learning using CT as a progression unit. This is open for more research.

10.4 Feasibility Study

A feasibility study was conducted on the basis of the ideas discussed in this chapter. An instructional resource package was developed for teaching NOS critically. The package included a NOS lesson that was prepared using the four steps described in the previous section. The health effects of low-intensity electromagnetic radiation from cell phones were chosen as a topic for students to engage in exploration of whether cell phone usage should be regulated by law. Two pieces of adapted primary literature were also developed, which were used as learning activities.

A framework proposed by Nistor et al. (2010) was used to study experienced science teachers' views of the resource package. The teachers were regarded as partners in the production of the resource. Nonetheless, not all feedback received from them led into product modularity, or changes in the resource as product. Some of the feedback was used to generate recommendations for in-service science teacher education.

Seventeen experienced secondary science teachers from three schools in Lebanon were enrolled in the study. The schools where the teacher worked offered the Lebanese as well as international programs and provided ongoing professional development opportunities for their teachers. The average duration of school teaching experience of the participants was 15.1 years, while their average duration of science teaching experience at the secondary level was 12.8 years.

The teachers participated in a 4-hour-workshop, led by the researcher, to get introduced to the draft resource. The researcher utilized a learning cycle to introduce the package. Next, teachers were asked to complete a questionnaire that contained a list of open-ended questions that aimed at collecting qualitative data to elicit feasible and nonfeasible features of the resource as well as recommendations for improvement. Semistructured in-depth interviews were also conducted with 16 participants. Interviews were audio recorded and transcribed. Questionnaires and interview questions were pilot-tested before being used. All data were coded and analyzed qualitatively using Miles and Huberman's (1994) approach.

The majority of the participants found the resource to be somewhat feasible for inclusion in a secondary-level science course (Table 10.1).

Table 10.2 shows the features of the resource that the participants thought made the lesson feasible and those that made it nonfeasible. Table 10.3 highlights every

Table 10.1 Number of participants who found the resource feasible, somewhat feasible, and nonfeasible

Categories	Number of participants
Feasible	1
Somewhat feasible	15
Nonfeasible	1

Table 10.2 The feasibility and nonfeasibility of features of the resource as identified by the participants

	Features																
Part.	rel	ali	nos	cri	eng	int	lan	dif	res	str	tim	pre	siz	con	ass	lev	rea
1	+	+							−		−					−	
2				−			+			+						−	
3		+							+		−						
4	+			−							−					−	−
5							+	+			−	−					
6	+			−			−	−			−					−	
7			+								−						
8	+					+								−			
9	+	−		+							−						
10		+	−			+					−			−			
11					+						−				−		
12				+							−			−	−		
13	−													−			
14			+	+										−			
15											−			−			
16		+									−	−	−				
17	+	−															

Note. rel relevant to students' lives, *ali* alignment (or its lack of) between curriculum and the resource, *nos* nature of science-related content, *cri* critical thinking, *eng* engaging, *int* interesting, *lan* language, *dif* difficulty level, *res* resources, *str* structure and organization of the lesson, *tim* time, *pre* preparation for teaching, *siz* class size, *con* controversial elements, *ass* assessment, *lev* learning levels and/or various needs of students in the same class, *rea* reading; + denotes a feature that makes the resource feasible; − denotes feature that makes the resource nonfeasible

feature concerning feasibility that was raised by at least four participants and illustrates sample responses. The number *four* was arbitrary and the rationale was based on the fact that about a quarter of the participants were pointing to that particular feature.

A number of features were identified through the teachers' recommendations, important to be considered when preparing similar resources and/or developing professional development programs. They are (1) relevance of the lesson to the lives of students; (2) alignment of the lesson with the science curriculum being used; (3) adaptation of the lesson, in general, and the background context, in particular, to the learning levels/needs of various students; (4) extent to which the lesson is engaging

Table 10.3 Sample participant responses concerning feasibility for each feature referred to by at least four participants

Features	fea+	fea−	Recommendations to make the lessons more feasible
rel	[The lesson is] related to our everyday life problems or issues that can somewhat enhance the curiosity of students to know more (Q4).	They [the studies] are projected onto a certain type of countries and cannot be generalized (Q13).	To generalize these studies (Q13).
ali	The idea of e.m.r. [electromagnetic radiation] is already mentioned in many physics books (Q10).	… it can't be applied in the course I teach (Q9, I9).	Include NOS objectives in the curriculum (Q1). Prepare different methods to start different chapters or topics (Q17).
cri	We can lead our students to critical thinking during explanation in class… (Q9, I9).	These lessons require analysis skills which some students might be weak at (Q2). Some students are not able to analyze articles, compare, and contrast results (I6).	To make the lessons feasible for everyone, the teacher should guide the students in all the parts especially those related to tables and drawing conclusions from data (Q2).
tim		…time limitations imposed by closed-ended curriculum set by the Ministry of Education (Q16).	Two teachers (eg biology and physics teachers) involved in one lesson? (Q1).
con		The contradictory conclusions reached even when based on the same data might confuse students (Q8). … they are not up to the level where they can manipulate different criteria. They need to memorize something (I8). … too controversial! Would leave students with the impression that science is not able to reach results conclusively (Q10, I10).	Select a less controversial idea, where we could teach the nature of science using much older research that is more conclusive than cellular phone usage which hasn't been studied enough (Q10).
lev		Presence of students with learning difficulties (e.g., dyslexic) (Q1).	Adapt the articles to students with learning difficulty who we believe we could do a great deal of critical thinking (e.g., more diagrams/pictures, less reading) (Q1).

Note. Definitions of features are found in Table 10.2; *Q* Questionnaire, number following Q represents participant number; *I* Interview, number following I represents participant number in nature; (5) involvement of scientific content knowledge; (6) involvement of NOS-related content; (7) involvement of elements that engage students in decision making; (8) discussions; (9) CT; (10) organization of the lesson; (11) details of the background context; (12) time limitations; (13) reading required from students; and (14) controversial elements involved in the lesson.

The study revealed a number of teacher challenges related to what CT is and how to teach for it. In addition, some participants found reading to be a challenge for their students. They suggested reducing the amount of reading and replacing it by other means. Such a position assumes that reading is considered merely a tool and is situated outside science rather than being inherent to the thinking process (Norris and Phillips 2003). Finally, controversial elements make the NOS lesson authentic. Nonetheless, many teachers considered their presence problematic. The view that students might lose trust in science as a result of being exposed to controversial issues is raised by science educators (e.g., Driver et al. 1996; Kolstø 2001b).

This study made possible a list of teacher-generated features helpful in designing similar instructional resources and in developing effective professional development modules for in-service teachers. The teachers' generally positive views provide grounds for optimism. The ideas developed in this chapter are worth pursuing further. They have the potential to be bases for research and development agenda.

References

Abd-El-Khalick, F. (2012a). Nature of science in science education: Towards a coherent framework for synergistic research and development. In B. J. Fraser, K. Tobin, & C. McRobbie (Eds.), *Second international handbook of science education* (pp. 1041–1060). New York: Springer. https://doi.org/10.1007/978-1-4020-9041-7_69.

Abd-El-Khalick, F. (2012b). Examining the sources for our understandings about science: Enduring conflations and critical issues in research on nature of science in science education. *International Journal of Science Education, 34*, 353–374. https://doi.org/10.1080/09500693.2011.629013.

Abrami, P. C., Bernard, R. M., Borokhovski, E., Wade, A., Surkes, M. A., Tamim, R., & Zhang, D. (2008). Instructional interventions affecting critical thinking skills and dispositions: A stage 1 meta-analysis. *Review of Educational Research, 78*, 1102–1134.

Akerson, V. L., & Hanuscin, D. L. (2007). Teaching nature of science through inquiry: Results of a 3-year professional development program. *Journal of Research in Science Teaching, 44*, 653–680. https://doi.org/10.1002/tea.20159.

Akerson, V. L., Abd-El-Khalick, F., & Lederman, N. G. (2000). Influence of a reflective explicit activity-based approach on elementary teachers' conceptions of nature of science. *Journal of Research in Science Teaching, 37*, 295–317. https://doi.org/10.1002/(SICI)1098-2736(200004)37:4<295::AID-TEA2>3.0.CO;2-2.

Akerson, V. L., Buck, G. A., Donnelly, L. A., Narguand-Joshi, V., & Weiland, I. S. (2011). The importance of teaching and learning nature of science in early childhood years. *Journal of Science Education and Technology, 20*, 537–549. https://doi.org/10.1007/s10956-011-9312-5.

Bell, R. L., Blair, L. M., Crawford, B. A., & Lederman, N. G. (2003). Just do it! Impact of a science apprenticeship program on high school students' understandings of the nature of science and scientific inquiry. *Journal of Research in Science Teaching, 40*, 487–509. https://doi.org/10.1002/tea.10086.

Driver, R., Leach, J., Millar, R., & Scott, P. (1996). *Young people's images of science*. Philadelphia: Open University Press.

Duschl, R. A., Schweingruber, H. A., Shouse, A. W., Committee on Science Learning, & National Research Council. (2007). *Taking science to school: Learning and teaching science in grades K-8*. Washington, DC: National Academies Press.

Ennis, R. H. (1989). Critical thinking and subject specificity: Clarification and needed research. *Educational Researcher, 18*, 4–10. https://doi.org/10.3102/0013189X018003004.

Ennis, R. H. (1996a). *Critical thinking*. NJ: Prentice Hall.

Ennis, R. H. (1996b). Critical thinking dispositions: Their nature and assessability. *Informal Logic, 18*, 165–182.

Ennis, R. H. (2018a). Critical thinking across the curriculum: A vision. *Topoi, 37*, 165–184.

Ennis, R. H. (2018b). *The nature of critical thinking*. http://criticalthinking.net/index.php/longdefinition/. Accessed online 19 Sept 2018.

Gunn, T. M., Grigg, L. M., & Pomohac, G. A. (2007). *Critical thinking in science education: Can bioethical issues and questioning strategies increase scientific understanding?* Paper presented at the ninth international history, philosophy & science teaching conference. University of Calgary. http://www.ucalgary.ca/ihpst07

Hitchcock, D. (2018). Critical thinking. In E. N. Zalta (Ed.), *The Stanford encyclopedia of philosophy (fall 2018 edition)*. Stanford: Stanford University. https://plato.stanford.edu/archives/fall2018/entries/critical-thinking/. Accessed online Sept 2018.

Keating, D. P. (1988). *Adolescents' ability to engage in critical thinking*. [S.l.]: Distributed by ERIC Clearinghouse.

Khishfe, R. (2008). The development of seventh graders' views of nature of science. *Journal of Research in Science Teaching, 45*, 470–496. https://doi.org/10.1002/tea.20230.

Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth graders' views of nature of science. *Journal of Research in Science Teaching, 39*, 551–578. https://doi.org/10.1002/tea.10036.

Kim, S. Y., & Irving, K. E. (2010). History of science as an instructional context: Student learning in genetics and nature of science. *Science & Education, 19*, 187–215. https://doi.org/10.1007/s11191-009-9191-9.

King, P. M., & Kitchener, K. S. (1994). *Developing reflective judgment: Understanding and promoting intellectual growth and critical thinking in adolescents and adults*. San Francisco: Jossey-Bass.

Kolstø, S. D. (2001a). Scientific literacy for citizenship: Tools for dealing with the science dimension of controversial socioscientific issues. *Science Education, 85*, 291–310. https://doi.org/10.1002/sce.1011.

Kolstø, S. D. (2001b). To trust or not to trust,… ' -pupils' ways of judging information encountered in a socio-scientific issue. *International Journal of Science Education, 23*, 877–901. https://doi.org/10.1080/09500690010016102.

Krajcik, J., Blumenfeld, P. C., Marx, R. W., Bass, K. M., Fredricks, J., & Soloway, E. (1998). Inquiry in project-based science classrooms: Initial attempts by middle school students. *The Journal of the Learning Sciences, 7*, 313–350. https://doi.org/10.1207/s15327809jls0703&4_3.

Kuhn, D. (1999). A developmental model of critical thinking. *Educational Researcher, 28*, 16–25+46. https://doi.org/10.3102/0013189X028002016.

Laudan, L. (1982). Commentary: Science at the bar-causes for concern. *Science, Technology & Human Values, 7*(41), 16–19.

Lederman, N. G. (2004). Syntax of nature of science within inquiry and science instruction. In L. B. Flick & N. G. Lederman (Eds.), *Scientific inquiry and nature of science* (pp. 301–317). Dordrecht: Kluwer.

Lipman, M. (2003). *Thinking in education* (2nd ed.). Cambridge: Cambridge University Press.

Matthews, M. R. (1994). *Science teaching: The role of history and philosophy of science*. New York: Routledge.

McComas, W. F. (Ed.). (1998). *The nature of science in science education: Rationales and strategies*. New York: Kluwer Academic Publishers.

McComas, W. F. (2004). Keys to teaching the nature of science. *The Science Teacher, 71*(9), 24–27.

Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook* (2nd ed.). California: SAGE.

National Research Council [NRC]. (1996). *National science education standards*. Washington, DC: National Academic Press. Retrieved from http://www.nap.edu/openbook.php?record_id=4962

Nicoll, B. (1996). *Developing minds: Critical thinking in k-3*. Paper presented at the California Kindergarten Conference, San Francisco, CA. Distributed by ERIC Clearinghouse.

Nistor, N., Dehne, A., & Drews, F. T. (2010). Mass customization of teaching and training in organizations: Design principles and prototype evaluation. *Studies in Continuing Education, 32*, 251–267. https://doi.org/10.1080/0158037X.2010.517996.

Norris, S. P., & Phillips, L. M. (2003). How literacy in its fundamental sense is central to scientific literacy. *Science Education*, *87*, 224–240. https://doi.org/10.1002/sce.10066.

Osborne, J., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. (2003). What "ideas-about-science" should be taught in school science? A Delphi study of the expert community. *Journal of Research in Science Teaching, 40*, 692–720. https://doi.org/10.1002/tea.10105.

Paraskevopoulou, E., & Koliopoulos, D. (2011). Teaching the nature of science through the Millikan-Ehrenhaft dispute. *Science & Education, 20*, 943–960. https://doi.org/10.1007/s11191-010-9308-1.

Roth, W. M. (1995). *Authentic school science: Knowing and learning in open-inquiry science laboratories*. Dordrecht: Kluwer.

Ruse, M. (1982). Creation science is not science. *Science, Technology & Human Values, 7*(40), 72–78.

Sadler, T. D. (Ed.). (2011). *Socio-scientific issues in the classroom: Teaching, learning and research*. Dordrecht: Springer.

Schwab, J. J. (1962). The teaching of science as enquiry. In J. Schwab & P. Brandwein (Eds.), *The teaching of science*. Cambridge, MA: Harvard University Press.

Schwartz, R. S., Lederman, N. G., & Crawford, B. A. (2004). Developing views of nature of science in an authentic context: An explicit approach to bridging the gap between nature of science and scientific inquiry. *Science Education, 88*, 610–645. https://doi.org/10.1002/sce.10128.

Siegel, H. (1988). *Educating reason: Rationality, critical thinking, and education*. New York: Routledge.

Tamir, P. (1983). Inquiry and the science teacher. *Science Education, 67*, 657–672. https://doi.org/10.1002/sce.3730670513.

Yacoubian, H. A. (2015). A framework for guiding future citizens to think critically about nature of science and socioscientific issues. *Canadian Journal of Science, Mathematics, and Technology Education, 15*(3), 248–260.

Yacoubian, H. A., & BouJaoude, S. (2010). The effect of reflective discussions following inquiry-based laboratory activities on students' views of nature of science. *Journal of Research in Science Teaching, 47*, 1229–1252. https://doi.org/10.1002/tea.20380.

Yarden, A., Brill, G., & Falk, H. (2001). Primary literature as a basis for a high-school biology curriculum. *Journal of Biological Education, 35*(4), 190–195.

Zeidler, D. L., Walker, K. A., Ackett, W. A., & Simmons, M. L. (2002). Tangled up in views: Beliefs in the nature of science and responses to socioscientific dilemmas. *Science Education, 86*, 343–367. https://doi.org/10.1002/sce.10025.

Chapter 11
The Nature of Science Card Exchange: Introducing the Philosophy of Science

William W. Cobern and Cathleen Loving

To engage individuals in thinking about the nature of science, a subject that many may find obscure and esoteric, a good introduction is a necessity. This chapter presents a learning game called *The NOS Card Exchange*, originally developed in 1991 (Cobern 1991a), which has been found effective in arousing student and teacher interest in the *philosophy of science*. Here we describe the materials needed for the game and how the game is set up and played. There are many thoughtful articles in the literature stressing the need for philosophically literate teachers of science at all school levels (e.g., Allchin 2013; Erduran and Dagher 2014; Andersen et al. 1986; Hodson 1985; Machamer 1998, 2002; Matthews 2015; Martin 1979), and for many years textbooks used in science and science teaching method courses have contained some material on this important topic. Nevertheless, science educators in the past have been concerned that an acceptable level of philosophical sophistication was not being reached within the ranks of science teachers, and consequently are concerned about views toward the nature of science promoted in the classroom (e.g., Shymansky and Kyle 1986). In 1988, Duschl summarized the classroom situation by saying that "the prevailing view of the nature of science in our classrooms reflects an authoritarian view; a view in which scientific knowledge is presented as absolute truth and as a final form" (p. 51; also see Duschl 2008). This view is called scientism, and one purpose for teaching the nature of science is for guarding against *scientism*. Nevertheless, concerns about teachers' understanding of the nature of science and about the epistemology and philosophy of science persist (Matthews 2015). This is a problem because as we learn more about students' worldviews, we begin to understand how the scientistic view extinguishes students' nascent interest

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_11

in science (Cobern 1991b, 1996). Moreover, those students who do accept the scientistic view are likely to become disenchanted with science later as science fails to achieve the unrealistic expectations accompanying a scientism orientation. Furthermore, failing to understand the epistemology and philosophy of science may exacerbate doubts pertaining to controversial areas of science such as evolution (NAS 1998) and climate change (Carter and Wiles 2014). The challenge is how to teach the philosophy of science to teachers with greater effectiveness.

11.1 The Card Exchange

In many schools, often early in the year, lessons are taught addressing the nature of science. The *Next Generation Science Standards* (NGSS 2016) has changed the language somewhat in that NGSS refers to the practices of science and engineering. However, within the NGSS concept of practices, there is descriptive information on the nature of science, and ideas pertaining to the nature of science are integrated into the NGSS standards. To the extent that the NGSS standards are employed by teachers, instruction on the nature of science could improve. However, the NGSS has been criticized for burying nature of science standards within the framework and thus in a sense undermining the importance of teaching the nature of science (McComas and Noushin 2016). In other words, it is not clear that the three-dimensional structure of the NGSS will lead to the sound teaching of the nature of science unless teachers understand the importance of epistemology within science. The concern then with NGSS is that gains in the teaching of the nature of science may be lost, and that teachers will revert to the practice of regarding the nature of science as little more than a method listed on the board and provided as *the* way all scientists work (i.e., the apocryphal scientific method). Or it may be suggested that students will be following various aspects of this method in numerous activities throughout the year in the form of NGSS science and engineering practices. Students are told, therefore, that they will be doing real science. We take the view that students' understanding of (a) what science is, (b) just how human the endeavor really is, and—perhaps equally important—(c) what science is not can be enriched and made more engaging by showing that those who do science, and those who write about it, hold varying views as to just what is authentic science (Grinnell 2009; Martin et al. 1990). Such a goal requires that teachers of science have some understanding of the philosophy of science.

If we can find ways to determine what individual students and teachers currently think, we can acknowledge their varying views—whether they come from ignorance, first impressions, or an extensive knowledge base about science. If necessary, preservice methods courses or in-service development activities can help students and teachers construct a more informed view of science. Our purpose in this chapter is to present a learning game that acts as a powerful *set induction* for subsequent instruction in the philosophy of science. We have found that this activity engages our students' minds and precipitates enthusiastic discussion on the question, "what is science all about?"

We have used the game discussed here successfully in a variety of settings. Elementary and secondary *preservice methods classes* are one example. Here we found our challenge to be how much time we can spend on the nature of science versus all the pedagogical and content issues one must deal with for a variety of science disciplines and a variety of grades preservice students will teach. We found that if students have only one science methods class, it is difficult to find the necessary time to do a good job with nature of science issues. It is always the struggle between our desire to give them the necessary background and their desire to know "what can I do in my classroom tomorrow." The card game does, however, serve as a highly effective entry into a world that many students do not know exists. Moreover, the game can also be used as part of in-service, teacher development work where the practicing teachers need help to further their understanding of the nature of science and its grounding in the philosophy of science.

We have used the card game with veteran *classroom teachers* at summer workshops and at state science teacher meetings in workshop settings. They love the activity. Many are surprised to discover new ideas about science about which they have not had much background or experience. "Light bulbs" often go on in these settings and some teachers crave more. We both have had, from time to time, this activity result in teachers later enrolling in our graduate courses which concentrate on the nature of science and science teaching. There is little indication that teachers who have become familiar with this strategy use the cards immediately with their students, although the high school teachers were more likely to see this as a possibility for their students in secondary settings. Instead, it appeared that they were seeing this as a self-enriching experience that might enable them to teach from a more informed perspective.

We have found that graduate students in science education who play the card game are potentially the best prepared to get the most out of this activity. These students tend to have good backgrounds in science, have taught for a number of years, and have combined that experience with recent course work and, for some, active research in current issues of science education reform. These students tend to have the most intense and detailed conversations, and their resultant paragraphs about science tend to be the most perceptive and balanced. Later in the course, they often return to some of these statements to design exhibitions for their peers about how they would teach this principle about science to students. For example, two graduate students designed five different posters depicting five well-known models of classification systems throughout the history of science from Aristotle to the present. Their peers loved it because it was such a vivid way to teach something all children learn in a developmental way. It so clearly showed these systems to be human constructions that were later replaced with what the scientific community decided were more authentic models. What better way to show that "science builds on what has gone on before and refines its conclusions" or "theory and observation interact" or "theories help scientists interpret their observations."

Finally, interesting results occurred when we used the card game with some university scientists. Scientists are diverse in their views about science—some holding rather strong empiricist views, others seeming theoretically driven, and others appearing balanced. The cultural component was minimally referred to by our scientists. The research piece to the card game—looking more closely at the relationship between composition (race, culture, gender) of our various card-playing groups and our results, what they do with the cards, how they respond to the activity initially and in retrospect, what they propose to do differently when they leave us, and what they end up doing back in their schools—is richly layered and ongoing.

This *card exchange* activity had its origins in a *learning game* developed by Bergquist and Phillips (1975) for classes of 20 students or more. We use the game much as it was originally developed except that the game content is changed to the philosophy of science (the Bergquist and Phillips game was designed to help college faculty "clarify and articulate their assumptions about teaching and learning," p. 23). Our game works well because at the beginning students are encouraged to move around and talk with each other, things almost all students like to do. The subject of conversation is the content of the cards. This works as a set induction because during their conversations, students quite naturally begin considering what they believe about science and how those beliefs may or may not coincide with what others believe. Later in the game students form groups based on the content of the cards they hold and then corporately produce a written summary. Both of these acts require compromise which forces the students to give a rough rank order to their beliefs about science. The result is that when we begin our part of the instructional process, our students are not only keenly aware that many of them hold quite different views on the nature of science, and many of them now have doubts about the validity of their own views. They are engaged.

11.2 Playing the Game

To prepare for this game, the teacher must develop a set of science statements related to what that teacher later wishes to accomplish with his or her philosophy of science instruction. A single statement is placed on each card. The statements should be succinct and easily understood. They should represent a broad range of viewpoints, including specific views to be expressed in the course. The set of card statements may be redundant. In fact, redundancy as well as diversity is necessary so that students can avoid being trapped with statements that they cannot affirm. We personally use a set of more than 200 cards containing 40 unique statements representing six categories (see Appendix for the actual statements):

- Theoretical emphasis: Science is primarily a rationalistic, theory-driven endeavor (e.g., see Hempel 1966; Krüger 1988; Popper 1968).
- Empirical emphasis: Science is primarily a data-gathering, experimental endeavor in pursuit of physical evidence (e.g., see Braithwaite 1955).

- Antiscience view: Science is overrated. One should not give much credence to the aims, methods, or results of science (e.g., see Appleyard 1992; Sale 1995; Skolimowski 1974; see also Holton 1993).
- Scientism: Science is *the* way of knowing; it is the perfect discipline (for critical reviews, see, e.g., Eastman 1969; Hughes 2012; Poole 1995; or Settle 1990; for supportive views, see, e.g., Harris 2011 or Hawking 2003).
- Cultural view: Science is embedded in a social, historical, and psychological context which affects all that goes on in science (e.g., see Cobern 1991b; DeWitt 2010; Fuller 1991; Harding 1993; Hodson 1993).
- Pragmatic view: This view point understands science to be a complicated affair that cannot easily be reduced to one or even a few simple descriptions (e.g., see Loving 1991, 1992; Cobern and Loving 2008).

The statements used in this activity (found in the Appendix) reflect the diversity found in current thought. They allow for comparison and contrast with our objective which simply put is science viewed as both empirical and theoretical; science as a powerful though limited way of knowing; science as a human, not mechanical endeavor; and science as a dynamic process. Depending on the instructor's objectives, other statements can be used. Our statements were drawn from many sources. In addition to those listed above, we refer the reader to AAAS (1993), Aicken (1984), Clayton (1997), Eastman (1969), Eflin et al. (1999), McGrew et al. (2009), Kimball (1967), Lange (2007), Loving (1991), Matthews (2015), and National Research Council (1996).

The game begins with the instructor giving each participant a randomly drawn set of six to eight cards. The participants will need 10–15 min to evaluate their cards according to what they can most and least affirm. They then have about 30 min in which to mill about examining each other's statements and making trades. Timing will vary with the number of participants and what time the participants feel that they need. The leader will need to assess what time is needed, but always sufficient time should be allowed for each participant to examine every other participant's cards. The goal is to improve one's hand by trading cards one for one; in other words, the participant's goal is to trade cards they like less for ones they like more. There is no discarding. At the end of trading we have everyone sit down while we give the next set of instructions. Instructions for each phase should not be given in advance.

In the second phase, participants are again to mill about, but this time seeking someone with whom they can pair. The pairing rules are that each pair must hold eight cards on which they have relative agreement. Each member of a pair must contribute at least three cards. This is important if the pairs are to be truly formed by compromise. The pair's remaining four cards are discarded.

Phase 3 of the game is a repeat of phase 2, except now the pairs form quadruplets. Each foursome is to hold eight cards, with each pair contributing at least three cards. Once the foursome has been established, the participants are asked to rank order their cards. Then if they wish they may discard the two bottomed-ranked cards. Based on this final set of cards, the participants cooperate to write a statement of paragraph length on the nature of science. The game concludes as the various groups share their paragraphs and to say why they accepted some statements while rejecting others. Generally, this is enough to precipitate vigorous discussion. We facilitate the discussion by writing on the board a few phrases that characterize the views being presented.

We follow up the discussion with a presentation of two *case studies* from the *history of science*. Typically, we use Ignaz Semmelweiss' work with childbed fever and Newton's exploration of the phenomena of colors (Mannoia 1980).[1] In these case studies, we look for examples of the statements on the nature of science that the participants have advocated in their card exchange summaries. The case studies can be presented orally in a recitation format by the leader or in the form of a printed handout. The advantage of using a handout is that the groups working individually to compare and contrast their card exchange summaries with the case studies do a more thorough job. The disadvantage is the amount of time required. The discussion of the card exchange summaries vis-a-vis the case studies concludes the set induction. From this point, we begin the main body of instruction on the nature of science.

11.3 Conclusion

We personally have found the card exchange activity to be an effective method of drawing our students into the philosophy of science, a subject they heretofore resisted. It capitalizes on the innate gregariousness of students and the diversity of opinion among students. A set induction is, however, only the beginning of a lesson. The effectiveness of what happens afterwards depends on how well one can hold the attention captured during the set induction. Obviously, there is a need for many creative instructional strategies if the philosophical preparation of preservice science teachers, or the professional development of in-service teachers, is to be effective.

Appendix: Card Exchange Statements

Theoretical Emphasis

1. Science is open-ended, but scientists operate with expectations based on the predictions of theory.
2. A theory is what scientists strive for: a large body of continually refined observations, inferences, and testable hypotheses.

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[1] For difficulties with the various retelling of the Semmelweiss story, see Allchin (2003).

3. Theories help scientists interpret their observations: facts do not speak for themselves.
4. In general, scientists plan investigations by working along the lines suggested by theories, which in turn are based on previous knowledge. Theories serve to give direction to observations, i.e., they tell one where to look.
5. A theory is a logical construct of facts and hypotheses that attempts to explain a range of natural phenomena and that can be tested in the natural world.
6. Good science cannot be done without good theories.

Empirical Emphasis

1. Observation is central to all of science, i.e., seeing is believing.
2. A scientist should not allow preconceived theoretical ideas to influence observation and experimentation.
3. Unless an idea is testable, it is of little or no use; thus, scientists attempt to convert possible explanations into testable predictions.
4. Careful, repeatable observation and experiment give the facts about the world around us.
5. Good science always begins with observations.
6. Science is never dogmatic; it is pragmatic—always subject to adjustment in the light of solid, new observations.
7. A phrase such as "Many scientists believe…" misrepresents scientific inquiry because scientists deal in evidence.

Antiscience View

1. Science is always changing and therefore is not very reliable.
2. Scientists should be held responsible for the harm their discoveries have caused, e.g., pollution and nuclear weapons.
3. Earning recognition from other scientists is really the main motivation of more scientists.
4. Most of what scientists do will never be of much practical value.
5. Money spent on projects such as NASA space flights would be better spent on healthcare for the needy.
6. Science destroys values and morality by disparaging the unique nature of men and women.
7. Science and religion are fundamentally at odds.

Scientism

1. The scientific method should be followed in all fields of study.
2. Scientists and engineers should make the decisions about things like types of energy to use because they know the facts best.
3. Science is the most important way of gaining knowledge open to humanity.
4. Science knowledge is of much greater value than any other type of knowledge.
5. Only science can tell us what is really true about the world.
6. Science knowledge is always objective and self-correcting.
7. Credit for our advanced way of life must go to science and scientific progress.

Cultural View

1. Funding influences the direction of science by virtue of the decisions that are made on which research to support.
2. The scientific enterprise is situated in specific historical, political, cultural, and social settings; thus, scientific questions, methods, and results vary according to time, place, and purpose.
3. The predominance of men in the sciences has led to bias in the choice and definition of the problems scientists have addressed. This male bias is also one factor in the underrepresentation of women in science.
4. Scientific facts are manufactured through social negotiations. Nature has nothing to say on its own behalf.
5. Scientists in one research group tend to see things alike, so even groups of scientists may have trouble being entirely objective.
6. The Early Egyptians, Greeks, Chinese, Hindu, and Arabic cultures are responsible for many scientific and mathematical ideas and technological inventions.
7. Until recently, some racial minorities, because of restrictions on their education and employment opportunities, were essentially left out of the formal work of the science establishment. The remarkable few who overcame these obstacles were even then likely to have their work disregarded by the science establishment because of their race.

Pragmatic View

1. Science is one of several powerful ways of knowing and understanding the natural world, however, some matters cannot be examined usefully in a scientific way.
2. Science leads to generalizations based on observations or theories. Science always aims to be testable, objective, and consistent.
3. As with all human endeavors, science is subject to many influences, both good and bad.
4. Science builds on what has gone on before and refines its conclusions, but scientific work does not result in infallible propositions, such as the word "proof" implies to a nonscientist.
5. Scientific progress has made possible some of the best things in life and some of the worst.
6. Theory and observation interact. Each contributes to the other: If theory without observation is empty, then observation without theory is blind.

References

Aicken, F. (1984). *The nature of science*. London: Heinemann Educational Books.
Allchin, D. (2003). Scientific myth-conceptions. *Science Education, 87*, 329–351.
Allchin, D. (2013). *Teaching the nature of science: Perspectives & resources*. Saint Paul: SHiPS Education Press.

American Association for the Advancement of Science (AAAS). (1993). *Benchmarks for Science Literacy: Project 2061*. New York: Oxford University Press.

Andersen, H. O., Harty, H., & Samuel, K. V. (1986). Nature of science, 1969 and 1984: Perspectives of preservice secondary science teachers. *School Science and Mathematics, 86*(1), 43–50.

Appleyard, B. (1992). *Understanding the present – Science and the soul of modern man*. New York: Anchor Books Doubleday.

Bergquist, W. H., & Phillips, S. R. (1975). *A handbook for faculty development*. Danville: Danville Press.

Braithwaite, R. B. (1955). *Scientific explanation: A study of the function of theory, probability and law in science*. New York: Cambridge University Press.

Carter, B. E., & Wiles, J. R. (2014). Scientific consensus and social controversy: Exploring relationships between students' conceptions of the nature of science, biological evolution, and global climate change. *Evolution: Education and Outreach, 7*(1), 1–11.

Clayton, P. (1997). Philosophy of science: What one needs to know. *Zygon, 32*(1), 95–104.

Cobern, W. W. (1991a). Introducing teachers to the philosophy of science: The card exchange. *Journal of Science Teacher Education, 2*(2), 45–47.

Cobern, W. W. (1991b). *World view theory and science education research* (NARST Monograph No. 3). Manhattan, KS: National Association for Research in Science Teaching.

Cobern, W. W. (1996). Worldview theory and conceptual change in science education. *Science Education, 80*(5), 579–610.

Cobern, W. W., & Loving, C. C. (2008). An essay for educators: Epistemological realism really is common sense. *Science & Education, 17*(4), 425–447.

Dewitt, R. (2010). *Worldviews: An introduction to the history and philosophy of science* (2nd ed.). Oxford: Blackwell Publishing Limited.

Duschl, R. A. (1988). Abandoning the scientistic legacy of science education. *Science Education, 72*(1), 51–62.

Duschl, R. A. (2008). Science education in three-part harmony: Balancing conceptual, epistemic, and social learning goals. *Review of Research in Education, 32*(1), 268–291.

Eastman, G. (1969). Scientism in science education. *The Science Teacher, 36*(4), 19–22.

Eflin, J. T., Glennan, S., & Reisch, G. (1999). The nature of science: A perspective from the philosophy of science. *Journal of Research in Science Teaching, 36*(1), 107–116.

Erduran, S., & Dagher, Z. R. (2014). Reconceptualizing the nature of science for science education: Scientific knowledge, practices and other family categories. In D. Zeilder (Ed.), *Contemporary trends and issues in science education*. Dordrecht: Springer.

Fuller, S. (1991). *Social epistemology*. Bloomington: Indiana University Press.

Grinnell, F. (2009). *Everyday practice of science: Where intuition and passion meet objectivity and logic*. Oxford: Oxford University Press.

Harding, S. (Ed.). (1993). *The "racial" economy of science: Toward a democratic future*. Bloomington, IN: Indiana University Press.

Harris, S. (2011). *The moral landscape: How science can determine human values*. New York: Free Press.

Hawking, S. W. (2003). *The theory of everything: The origin and fate of the universe* (p. 2003). Beverly Hills: Phoenix Books.

Hempel, C. G. (1966). *Philosophy of natural science*. Englewood Cliffs: Prentice Hall.

Hodson, D. (1985). Philosophy of science, science and science education. *Studies in Science Education, 12*, 25–57.

Hodson, D. (1993). In search of a rationale for multicultural science education. *Science Education, 77*(6), 685–711.

Hughes, A. L. (2012). The folly of scientism. *The New Atlantis, 37*, 32–50.

Kimball, M. E. (1967–1968). Understanding the nature of science: A comparison of scientists and science teachers. *Journal of Research in Science Teaching, 5*, 110–120.

Krüger, L. (1988). How philosophy and science came to differ. In E. Ullmann-Margalit (Ed.), *Science in reflection: The Israel Colloquium: Studies in history, philosophy, and sociology of science Volume 3 (110)* (pp. 37–50). Dordrecht: Springer.

Lange, M. (Ed.). (2007). *Philosophy of science: An anthology*. Oxford: Blackwell.

Loving, C. C. (1991). The scientific theory profile: A philosophy of science models for science teachers. *Journal of Research in Science Teaching, 28*(9), 823–838.

Loving, C. C. (1992). From constructive realism to deconstructive anti-realism: Helping science teachers find a balanced philosophy of science. In *History and philosophy of science in science education, Vol II, Proceedings of the second international conference on the History and Philosophy of Science and Science Teaching Queens University*, Kingston, Ontario, Canada.

Machamer, P. (1998). Philosophy of science: An overview for educators. *Science & Education, 7*(1), 1–11.

Machamer, P. (2002). A brief historical introduction to the philosophy of science. In *The Blackwell guide to the philosophy of science* (pp. 1–17). Malden: Blackwell Publishers Ltd.

Mannoia, V. J. (1980). *What is science?: An introduction to the structure and methodology of science*. Washington, DC: University Press of America.

Martin, M. (1979). Connections between philosophy of science and science education. *Studies in Philosophy and Education, 9*, 329–332.

Martin, B. E., Kass, H., & Brouwer, W. (1990). Authentic science: A diversity of meanings. *Science Education, 74*(5), 541–554.

Matthews, M. R. (2015). *Science teaching: The contribution of history and philosophy of science*, 20th Anniversary Rev and Exp Ed. New York: Routledge.

McComas, W. F., & Noushin, N. (2016). The nature of science and the next generation science standards: Analysis and critique. *Journal of Science Teacher Education, 27*(5), 555–576. ISSN:1573-1847.

McGrew, T., Alspector-Kelly, M., & Allhoff, F. (2009). *Philosophy of science: An historical anthology*. Malden: Wiley-Blackwell.

National Research, C. (1996). *National Science Education Standards*. Washington, DC: National Research Council.

National Academy of Sciences. (1998). *Teaching about evolution and the nature of science*. Washington, DC: National Academy Press.

Next Generation Science Standards. (2016). *Next generation science standards* [Web Page]. http://www.nextgenscience.org/ [2016, May 4].

Poole, M. W. (1995). *Beliefs and values in science education*. Philadelphia: Open University Press.

Popper, K. R. S. (1968). *Conjectures and refutations: The growth of scientific knowledge*. New York: Harper & Row.

Sale, K. (1995). *Rebels against the future: The luddites and their war on the industrial revolution – Lessons for the computer age*. Reading: Addison-Wesley.

Settle, T. (1990). How to avoid implying that physicalism is true: A problem for teachers of science. *International Journal of Science Education, 12*(3), 258–264.

Shymansky, J. A., & Kyle, W. C., Jr. (1986). A summary of research in science education – 1986. *Science Education, 72*, 254–275.

Skolimowski, H. (1974). The scientific world view and the illusions of progress. *Social Research, 41*, 52–82.

Chapter 12
Reflecting on Nature of Science Through Philosophical Dialogue

Lynda Dunlop and Jelle de Schrijver

12.1 Introduction

Nature of science (NOS) entails the philosophical (epistemological and ontological) underpinnings of science such as its levels of uncertainty, its realm and limits, its biases and the reasons for its reliability (McComas and Kampourakis 2015; Lederman 2006). NOS education can play a key role in stimulating the scientific literacy of students (Miller 1998) while positively impacting their often naïve conceptions about science (Clough 1997). Yet, there lingers a conflict in the science curriculum; on the one hand, the aim is to teach about scientific knowledge (scientific findings, concepts and theories), but on the other hand, the aim is to teach about the nature of science contextualizing and questioning the objectivity of this scientific traditional science content. It is therefore not surprising that tackling the philosophical underpinnings of NOS and its underlying multiperspectivity can be challenging for science teachers. To overcome this problem, in this chapter, we will explore how philosophical dialogue can contribute to *reflection* about and understanding of the nature of science among students and can help science teachers to deal with uncertainties. We will discuss the potential of philosophical dialogue to stimulate learning about the nature of science through sharing our approaches with examples and drawing on research literature relating to *philosophy for children* more broadly, and specifically in a scientific context.

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_12

12.2 Nature of Science and the Importance of Reflection

Teaching about the nature of science helps to clarify and contextualize the processes used to obtain reliable knowledge. It tackles themes such as the tentativeness of scientific findings, the subjective role of the researcher or the existence of different scientific methods. In short, it tackles the special way in which scientific knowledge is formed, it is concerned with science as a human enterprise and discusses the tools and products of science (McComas 2015).

As explicit and reflexive teaching of the nature of science is central to enable students to develop understandings of NOS (Lederman 2006), it follows that teaching NOS does not entail only lecturing, but rather implies designing lessons to address NOS issues where students construct a proper understanding of and make connections between what they experience and the NOS issues at hand (Khishfe and Abd-El-Khalick 2002). One of the ways to stimulate *reflection* about the nature of science may be to confront students with the complex nature of NOS itself. Though different characteristics of NOS are uncontroversial, other aspects are contextual and have complex exceptions (Clough 2006). For instance, though scientific knowledge is always tentative, some scientific findings or theories are more probable and more reliable than others, implying that the tentativeness of science differs with respect to the domain that is under scrutiny. Furthermore, philosophers of science often fundamentally disagree about the claims of the nature of science—for instance, the (anti-)realism debate regarding the ability to obtain truth (see, e.g. Chakravartty 2011). Thus, to stimulate students' *reflection* about the nature of science, teaching the nature of science may imply conveying a plurality of views—multiperspectivity—challenging the student to discuss and explore the often unchartered territory hidden under the regular science curriculum (Clough 2006). *Philosophical questions* about science can be starting points to spark these explorations, confront students with complexities and allow *discussion* and active involvement of the students. In this chapter, we will explore how *philosophical dialogue* will enable *reflection* among students about the nature of science.

12.3 An Introduction to Philosophical Dialogue

One of the key distinctions between science and humanities education, according to philosopher Matthew Lipman (2003), is the way in which knowledge is presented, with science textbooks presenting scientific knowledge as though settled. In contrast, in the humanities knowledge is treated as intrinsically problematic, so students are encouraged to look for new problems of interpretation or conceptualisation rather than apply standard methods of problem solving to new problems (Donnelly 2004). The humanities, including *philosophy*, offer approaches for teaching the nature of science, which has different characteristics to curriculum content focused on scientific ideas. One such approach is the management of *philosophical dialogue* between young people, an approach derived from Lipman (1977).

Lipman's approach to doing *philosophy* with children is to begin with a shared story, read aloud, which purposely contains problematic, contested philosophical ideas, typically presented from the perspective of fictional characters in real-life situations. These philosophical novels such as *Harry Stottlemeier's Discovery* (Lipman 1977) model the process of philosophical *inquiry*, from feelings of difficulty and doubt, to formulating a problem, identifying concepts, trying out ideas, offering evidence and examples and making judgments. After reading these stories aloud, children are encouraged to explore *philosophical questions*, as a group, in response to the stories. Each chapter of Lipman's novel is linked to a set of philosophical exercises associated with the text in accompanying manuals for teachers. These manuals support teachers to encourage philosophical *inquiry* with their students by integrating cognitive skills and conceptual content. For example, following Harry's (the protagonist) discovery about the structure of logical statements (the rule of conversion in the context of planets, but then applied more broadly), there follow exercises in application, e.g. in how to construct logical statements, testing what happens when subjects and predicates are reversed in different types of logical statement. These are not usually in a scientific context, although *Harry Stottlemeier's Discovery* does introduce concepts such as discovery, invention and truth. There has been growing interest in the practice of philosophical *inquiry* in a scientific context (see, e.g. Sprod 2011; Dunlop 2012; de Schrijver et al. 2015) and in the production of materials to support such practice.

Philosophical *inquiry* and scientific inquiry are distinct processes, and quite different strategies are required to address *philosophical questions* such as those associated with the nature of science; those which are more akin to humanities teaching than science teaching; and with which science teachers may have little experience. Levinson and Turner (2001) contrast the greater confidence and skill of humanities teachers in these teaching techniques, yet call for controversial or contested issues to be dealt with in science lessons because of the in depth scientific knowledge required to do them justice. Ratcliffe (2007) found that even experienced teachers often find it uncomfortable to address uncertainty and that they (i) feel the need to provide students with neatly tied up answers at the end of the lesson, (ii) are unable to focus on process as a learning outcome and (iii) avoid *discussion* because the situation is perceived as too complex. Donnelly (1999) also found that science teachers placed stronger emphasis on content knowledge, with uncertainty perceived as threatening, in contrast to history teachers who placed children's interpretations and judgements at the centre of teaching. This means that science teachers find it more difficult than humanities teachers to address issues, which have no clear-cut answers, but rather rely on complex and value-loaded issues questioning and contextualizing the objectivity and reliability of knowledge. *Philosophical dialogue* exactly helps to overcome this issue: it allows science teachers to embrace uncertainty, put children's ideas at the centre and problematize (scientific) knowledge, methods and cultures. When facilitating philosophical *inquiry*, it is important for the teacher to embrace uncertainty and recognize that there are times where there is a lack of consensus.

'Doing' *philosophy* can take many forms—whether based on exercises as in Lipman's example or whole class dialogue facilitated by the teacher, more common internationally. This type of dialogue takes different forms. Examples include Socratic dialogue, modelled on dialogue as questioning and Menippean dialogue, modelled on dialogue as creative play (Fisher 2007). Recent research in the UK has found evidence that doing *philosophy*, specifically the model proposed by SAPERE (the Society for the Advancement of Philosophical Enquiry and Reflection in Education), has a positive impact on cognitive ability, attainment at the end of primary school and on self-esteem and confidence (Gorard et al. 2015). An earlier study by Sprod (1998) found improvements in students' scientific reasoning as a result of participating in philosophical dialogue. Our interest is in the application of this approach to teaching NOS. The approaches we use are based on more explicitly scientific problems, scenarios and situations as the stimulus for generating *philosophical questions*. These questions are then discussed in an inquiry, facilitated by the teacher. *Philosophy for children* in the context of science can help students to develop their capability to ask questions, reason with logical coherence and consistency, make interpretations and form and test hypotheses (Gazzard 1993). It can further help students create meaning by encouraging them to clarify concepts and to link scientific ideas with other ideas (Sprod 2001). In doing so, students engage in argumentation which is a core characteristic of science (Duschl and Osborne 2002).

The approaches to *philosophical dialogue* presented next have been used with young people aged 9–19 (e.g. Dunlop et al. 2011) and are currently being piloted with in-service and pre-service teachers. The three main strategies we focus on are creating *philosophical questions*, facilitating *philosophical dialogue* and sustaining *philosophical dialogue*. *Philosophical dialogue* is by its nature open and informed by the participants, their knowledge and experiences, so the focus for the teacher is in creating the philosophical space and facilitating the dialogue such that arguments are present and critiqued, concepts and positions are clarified and the group gains insight into the issue. As such, it does not make sense to detail the philosophical arguments here as these are likely be different for each group. Much of the *discussion* focuses on questions as these are the fundamental basis for *philosophical dialogue* and an important strategy for the teacher facilitating the dialogue.

12.3.1 Beginning the Dialogue: The Centrality of Questions

Philosophical dialogue begins with a question. *Philosophical questions* can be described as those that are 'open to informed, rational and honest disagreement… possibly constrained by empirical and logico-mathematical resources, but requiring noetic resources to be answered' (Floridi 2013), i.e. to be open and to lend themselves to authentic exploration through reasoning. In our approach to NOS, we ask students in a group to explore *philosophical questions* as a community of inquiry in which the teacher acts as a facilitator. We discuss the role of the facilitator below.

Using *philosophical questions* (e.g. is a virus alive, how can we know what an atom is made of, and can scientific knowledge ever be proven?) as the focus for inquiry allows students to explore, discuss and develop their own ideas about the nature of science. These questions can originate from the children, or from the teacher. Interaction between the participants and facilitation by the teacher enables students to reflect upon the nature of science and develop their own arguments. The following section explains how to encourage children to create *philosophical questions*.

12.3.1.1 Distinguishing Philosophical Questions from Scientific Questions

Of course, children are familiar with questions in the context of their science lessons, but it is important to distinguish between *philosophical questions* and scientific questions and know when to adopt a scientific approach and when a philosophical approach is more appropriate. A useful way to start a sequence of philosophical inquiries is to ask children to sort questions into two groups, scientific questions and *philosophical questions*, then to distinguish their characteristics and to identify any troublesome questions that do not fit well into either category. Table 12.1 provides example questions for a card sort activity. Students are asked to distinguish between scientific questions, and non-scientific questions, and in so doing to discuss the characteristics of their two sets of cards. It is important to ask the children not to attempt to answer the questions on the cards, but rather to think about:

- Is the question a scientific question?
- What makes it scientific?
- What do the other questions have in common?

This task can help set the scene for a series of philosophical inquiries by helping children to identify necessary and sufficient conditions for a question to be considered scientific, which helps them in turn to explore what science is and to understand the limits of science: that scientific methods cannot be used to answer all questions. It can also support them to articulate what a *philosophical question* is, an understanding that they will need if they are asked to create their own *philosophical questions* (see Sect. 12.3.1.2).

At this point, it can be useful to identify some of the characteristics of questions that are most suitable for inquiry, e.g. can be answered from different perspectives, are not factual and require reasoning rather than empirical data collection.

Table 12.1 Distinguishing between scientific and *philosophical questions* using a card sort.

What is the chemical composition of water?	Why is the sky blue?
What are species?	What is the difference between a scientist and a magician?
How do scientists know they are right?	Is it possible to know how plants evolved?
Can a robot be a scientist?	Can two different scientific answers be true?
Is the big bang the best theory for how the universe started?	What happens when an acid is added to an alkali?
How did life on Earth begin?	Is there a scientific theory that will always remain true?

12.3.1.2 Stimulating Philosophical Questions

In creating the environment for *philosophical dialogue,* a range of approaches to question generation exists. This includes (a) development and/or selection of the question by the teacher/facilitator and (b) creation and/or selection of the question by the students.

Creation and/or selection of the question by students might be important when the teacher wants to:

1. Engage students with making connections between science, themselves and the world.
2. Give students ownership of the inquiry and ensure that the philosophical *inquiry* is relevant to them and to the science.
3. Develop their ability to ask *philosophical questions* and distinguish these from other types of question. The risk associated with such an approach is that the children do not ask questions that are explicitly about the NOS, but it is always possible for the teacher to prompt for these issues using Socratic questions such as *how do you know?*

Where students are tasked to create the *philosophical questions* which form the basis for an inquiry in this case, a stimulus material can be useful as a prompt. Scientific stimuli may include short practical demonstrations or practical work, extracts from plays such as *Life of Galileo* (Brecht 1986), short videos, songs, cartoons or texts. Typically, the stimulus material is shared with the group, and students asked to reflect on what they have seen, read, heard or shared. This might include identifying troublesome concepts, responding to the stimulus in a limited number of words, or asking children to identify ideas that they agreed or disagreed with. Following this *reflection*, students are asked to generate a *philosophical question*, which will be discussed by the group.

The careful selection of stimulus material and subsequent creation of *philosophical questions* enables students to explore their own questions relating to the nature of science, including how scientific knowledge is created and validated by the community, the limits of science, and the socio-ethical issues associated with new scientific knowledge and its applications. This enables the group to focus on questions of relevance not only to the nature of science, but to their own lives and experiences.

Creation and/or selection of the question by the teacher/facilitator might be important when there is a specific question or issue that the teacher would like for the class to explore, e.g. what is the difference between science and technology? What do biology and physics have in common? This may yield *philosophical dialogue* that focuses tightly on what teachers want their students to learn, but students may lack ownership of and investment in questions that have been selected for them.

To explore what it means to do science and be a scientist, a group was asked to consider ‘is a rabbit a scientist?’ The types of responses returned included:

- The characteristics of a scientist compared with those of rabbits.
- What can be known about rabbits.
- Features of scientific methods.
- The importance of solving problems in the world.
- Striving for a better understanding of the world.
- The nature of research more broadly.
- Motivation(s) of scientists.
- Experimentation and observation.
- Inductive and deductive reasoning.
- Intentionality of acting and self-awareness.
- Inter-generational communication methods.
- The accumulation of knowledge and ‘standing on the shoulders of giants’.
- Creative and critical thinking and logic.
- Science in the private and public sectors, and how science is funded.

Discussion of this playful *philosophical question* allows students to identify for themselves the tools and products of science, e.g. the role of observation, induction and deduction and the human products of science, such as creativity and social and cultural elements, as well as to practice logic by identifying characteristics of scientists and rabbits and identifying non-overlapping characteristics.

12.3.1.3 Questioning the Questions

The starting point for any philosophical *inquiry* is a *philosophical question*. Where young people create their own questions, it is often useful to question the question: first of all, to ensure that the questions under consideration are *philosophical questions*, open to exploration in this class, and distinguish these from scientific questions. It can also be useful to discuss what knowledge or ideas might be needed to address the question, or to create an agenda to identify the most important question. This helps students to understand the nature of *philosophical questions* and gives them the opportunity to think about what is important and why, areas of knowledge that they can bring to the topic and those which would require further research or background reading. Additionally, it is useful to ask whether there are connections between the questions—this encourages students to link ideas and have empathy with others.

For example, following a cartoon based on a news story about threats to the Cavendish banana (the dominant variety grown worldwide), one group of students produced the following questions:

- Why are bananas yellow?
- Does it matter what happens to bananas?
- Why do bananas get disease?
- Should we clone bananas?
- Why are dangerous chemicals used on bananas?
- Will bananas become different in the future?
- Should pesticides be used?

It should be noted that the questions are entirely determined by the children, and their priorities and interests—the same stimulus used with another group is likely to raise quite different questions. These questions are not all *philosophical questions*, and they focus on different, but linked, scientific topics (cloning, pesticides, disease transmission, use of pesticides). These questions demonstrate the potential for inter-disciplinary inquiry (involving ethics, chemistry, biology and physics), drawing on ideas about disease transmission, reproduction, pesticides, the theory of evolution, food chains and webs, or intensive and organic farming, depending on the question selected. These allow major elements of the nature of science such as socio-cultural influences on science, the importance of evidence in informing decisions which involve scientific dimensions. It is the role of the facilitator to ensure that the dialogue that stems from these questions is philosophical, which they can achieve by linking their questions to elements of NOS: e.g. what are the social and cultural influences at play here? What evidence would you need to make a decision?

Different methods can be used to determine the final question for philosophical *inquiry*. This can be selected by the group, using different methods, e.g. blind voting (no-one sees how anyone else votes), multivote (each person has several votes they can use as they want) or voting with your feet (each person stands next to the question they want to discuss). Following the selection of the question (however this is achieved), the children then participate in *philosophical dialogue*, facilitated by the teacher.

The important point to note is that the teacher's role in facilitating *philosophical dialogue* is not to teach pre-established ideas about the nature of science but rather to enable students to develop their own ideas about the nature of science.

12.3.2 Facilitating Philosophical Dialogue

In *philosophical dialogue* the teacher takes on a different role that the typical one: as a facilitator of the dialogue. The facilitator's role is to create the environment for the *philosophical dialogue* to happen (Palsson et al. 1999), to model skilful thinking (Sprod 2001), to focus *discussion* and to encourage deep consideration of the topic through the use of procedural questions (Gardner 1996). In the context of their review of how teachers can enable a good quality *discussion* in science, Levinson et al. (2012) also highlight the role of the teacher in promoting critical inquiry and developing students' reasoning skills and as a knowledge resource.

This philosophical approach demands that the teacher does not contribute substantially to the dialogue but rather enables the children to do so by asking procedural questions which encourage children to evaluate claims. Worley (2016) argues that an important dimension to *philosophical dialogue* is the dialectic: the systematic investigation, examination and evaluation of claims and options using questioning. Questions that the teacher can ask to encourage this include:

- Do you agree? (encourages engagement with and evaluation of another person's argument).
- Why do you think this? (seeking evidence and argument).
- What might people who disagreed with you say? (identifying counterarguments).
- What alternatives are there? (creative thinking, suggesting possibilities).
- What would make you change your mind? (non-dogmatism, identifying limitations).
- Is this always true? (limits to knowledge).

Other strategies which may be useful in facilitating *philosophical dialogue* are to encourage the use of Venn diagrams to identify relationships between groups and ideas (e.g. in the rabbit/scientist example above) and the identification of necessary and sufficient conditions. These questions and activities make students' thinking explicit and encourage them to think deeper about the special nature of scientific knowledge, the tools and products of science and the human elements of science. It is important to address these epistemological issues in science education, so that students understand how science legitimizes its knowledge claims (Osborne 1996) and understand the reasons we believe as we do (Osborne and Dillon 2010).

12.3.2.1 Stimulating Philosophical Dialogue

The examples that follow exemplify how four contexts (historical, contemporary, personal and the non-school setting) can be used to stimulate *philosophical dialogue*. Each of these examples prompt students or teachers to create philosophical questions and act as a context for stimulating *philosophical questions*, which ensures the link between the individual, science and the philosophical dimensions.

Example 1: Historical Contexts for Philosophical Dialogue Stories from the history of science, which examine personal, social, economic and political influences on the direction of scientific research, can be a good source of rich *philosophical questions* about how science is done, and about the uses (and abuses!) of science. Stories can be told in different ways, including by reading a text such as the play *Einstein's Gift* (Thiessen 2009), based on the story of Fritz Haber or showing a film,

Table 12.2 DNA discovery story as a stimulus for *philosophical dialogue*.

Friedrich Miescher was the first person to isolate the chemical we now know to be DNA from cells. He had been trying to purify proteins in white blood cells (collected from pus in old bandages sent to him from a clinic) but noticed a chemical that did not behave like a protein. He realised he had discovered a new chemical (DNA) and later found the same chemical in other types of cell	Linus Pauling used a new method of model-making to create 3D molecular structures to propose (incorrectly) that DNA was a triple helix. He built his model using known molecular distances and bond angles, with the knowledge that helical molecular structures were possible
Maurice Wilkins initial work on DNA showed that it could be crystallised for study by X-ray diffraction. He discussed the structure of DNA with Crick and Watson, showing them Franklin's image and helping them to interpret it. He later used X-ray crystallography to confirm and refine Watson and Crick's double helical structure for DNA	Erwin Chargaff discovered, using paper chromatography, that DNA had a different composition in different species: The bases appeared in a different order. He also found that no matter what species DNA came from, the number of purines was equal to the number of pyrimidines, and in particular that the amount of adenine (A) was equal to the amount of thymine (T) and the amount of guanine (G) was always equal to the amount of cytosine (C)
Rosalind Franklin studied DNA using X-ray crystallography. She prepared DNA samples and took the X-ray photograph that demonstrated that DNA was a helix in shape. She deduced the dimensions of DNA strands and that the phosphate groups were on the outside of the molecule. Her X-ray photo was shown to crick and Watson, who said that it was key to them discovering the structure of DNA when they did	James Watson and Francis crick used Pauling's modelling method and Franklin's X-ray photograph and measurements of DNA (given to them by Wilkins without her consent) to solve the structure of DNA. Using card cut-outs, they built DNA as a helix containing two strands connected with hydrogen bonds. Bases (A, T, G and C) are attached to sugars on a backbone. The backbone is made of sugars and phosphate groups. The 'rungs' of DNA are made of bases. A is always paired with T and G is always paired with C

e.g. *Life Story* (a feature film based on Watson's account of the discovery of the structure of DNA). The activity below (Table 12.2) asks students to read the contribution of individuals to the discovery of the structure of DNA: the example provides a summary of the contribution of seven individuals. Working in small groups, students are asked to (1) rank the contributions in order of importance on the pyramid grid and (2) discuss their justifications. They could also be asked to find out how the work of each of the scientists is related to each other by making a relational map. To do this, students stick each of the cards to a larger page and draw lines between related contributions, with details written on the line about how the work is related. Such an activity draws out both the human elements in science and the tools and products of science.

Following the activity, students in their groups are asked to feedback key concepts they have discussed. In our experience, the typical concepts that arise include competition, collaboration, reward, reputations, the importance of individuals and communities of scholars and the role of publication. These then lend themselves to generating *philosophical questions* for *discussion*, such as: who discovered the structure of DNA? What is intellectual property? What is the relationship between competition and collaboration in science? Is it ever right to use someone's work if they haven't consented? Is it important to recognise and reward individuals for scientific discoveries? What makes a good scientist? This format can be used in other historical contexts, e.g. the discovery of the structure of the atom or the structure of the solar system. Further approaches to the use of history of science that could be used as a basis for *philosophical dialogue* can be found in McComas and Kampourakis (2015). It is important for the teacher facilitating the *philosophical dialogue* on stories from the history of science to be well informed not only about the history of science in question but also about the key aspects of NOS at play.

These clearly relate to human elements of science, including the importance of creativity and social and cultural influences, but also the tools and products of science (this story represents different methods of problem solving: chemical analysis, modelling, imaging) and the role of theory, as well as the distinction between theories and hypotheses. Teachers have reported that this activity helped their students learn about the history of science and allowed them to engage emotionally with the topic and that they felt that this was more interesting for the students.

Example 2: Contemporary Contexts for Philosophical Dialogue Advances in contemporary science are a rich source of *philosophical dialogue* about science and its relationship to technology. *Philosophical dialogue* in relation to novel discoveries and applications in relation to, e.g. the machine/human interface or biotechnology can highlight the tentative but durable nature of scientific knowledge and the limits to science. For example, many technological innovations generate both new scientific questions and ethical questions, which cannot be answered using scientific methods or knowledge. Dealing with the latter is increasingly important as these innovations are frequently ahead of policy and public debate.

In terms of generating *philosophical dialogue* about contemporary contexts into the classroom, popular science magazines and newspapers are good stimuli for contemporary science ideas, providing they are accurate, and where relevant, include sufficient evidence to provide an informed basis for *discussion*. One example we have used relates to the use of medicines to interfere with memories. We started by identifying some uses of drugs more broadly, asking students to classify which uses were permissible, and which weren't, and to identify the criteria they used to decide:

- An athlete using steroids to heal an injury.
- An athlete using steroids to improve performance during training.
- A government giving citizens LSD without their knowledge to study their reactions.
- A student drinking an energy drink containing caffeine to stay awake to study.
- Former soldiers taking a medicine to help remove the fear associated with traumatic past events.

- A smoker using e-cigarettes containing nicotine to help them stop smoking.
- A person using medicines for off-label uses.
- Pilots in an army taking amphetamines to remain alert.

We then looked at the specific example of the use of the beta-blocker propranolol to remove the fear response associated with traumatic events. To think about the different perspectives on this, we use the question compass, in which students are asked to create at least four questions (1 for each of the cardinal compass points: for N about **N**ature; for W, **W**ho decides (political); East is about **E**conomic or **E**thical considerations; and finally S deals with **S**ocial issues. This encourages students to think about the impact of social, cultural and other elements on science. This particular example raised questions including the use of animals and humans in pharmaceutical research, the relationship between memories and identity, the structure, regulation and funding of pharmaceutical research, and issues associated with witness testimony in court. While not all of these questions relate directly to science, they do highlight the questions that scientific advances raise in society more generally, and the importance of considering multiple perspectives when making decisions about science.

Example 3: Personal: Critical Incidents in Practical Science As well as looking externally for stimuli relating to the nature of science, young people's own experiences can be a stimulus for philosophical *inquiry*. For example, critical incidents in the lab or classroom can be the starting point for philosophical *discussion*. In this context, a critical incident is an event which has significance in terms of provoking a pause for *reflection* about, e.g. values, attitudes or behaviour, for the student or teacher.

Practical science presents many opportunities for philosophical *discussion*. For example, where students obtain unexpected results (the relationship between theory and observation), or in the disposal of reagents (the impact of science on the environment). These incidents can be the source of *philosophical questions* for the basis of *philosophical dialogue* between students.

Example 4: Non-school Settings for Philosophical Dialogue About Science Also, non-school settings, such as (history of) science museums, can provide opportunities to teach about the nature of science (de Schrijver 2016). For instance, a combination of a workshop and a dialogue can lead to *reflection* upon NOS. After participating in a workshop where students make a small microscope in the tradition of the Dutch scientist Van Leeuwenhoeck, students can be motivated to ponder upon the question: ‘Can a scientist see without making an interpretation?’ A picture of a sperm cell that was drawn in the eighteenth century containing a homunculus can further motivate the students to participate in the thinking process about perception and interpretation, i.e. how scientists create meaning from their observations. This can be related to students' own practical experience in science: how do they make interpretations from their observations?

Facilitator: Can a scientist see without making an interpretation?
Student 1: No, a scientist who sees a homunculus in a sperm cell shows that scientists are always interpreting and can never just see.
Facilitator: What do you mean by interpretation? Can you give a definition?
Student 1: Interpreting means that you explain what you can see.
Facilitator: Does everyone agree that a scientist is always interpreting?
Student 2: I disagree. I think that only bad scientists don't make the difference between thinking and perceiving.
Facilitator: Why do you think so?
Student 2: Because a scientist can only know something if he watches the world without prejudices.
Facilitator: Can you give an example?
Student 2: For a long time people thought that fossils were ancient monsters. Only by leaving the prejudice that there can be monsters, scientists were able to discover the truth about fossils.
Facilitator: Does everyone agree?

12.3.3 Sustaining Philosophical Dialogue

Philosophical dialogue is different from dialogue in science. It is important to point out that *philosophical dialogue* requires sustained practice, over an extended period, and the creation of a philosophical space. There is often an initial discomfort as students become familiar with identifying and experiencing uncertainty, developing an argument and thinking about the reasons and evidence that they believe as they do. It can take students time to adapt to thinking philosophically about science, and the teacher needs to create the space for open, *philosophical dialogue* that is challenging yet supportive, and which often does not directly teach curriculum content.

12.4 A Note on Student Experiences

We have found that young people have enjoyed *philosophical dialogue* and found it interesting. They report that they learn—not just about science and how it works but also about what their peers think about substantive issues and how to make an argument. Teachers have reported that ongoing *philosophical dialogue* has improved listening, helped students gain confidence and become more involved in lessons, and to think more critically and creatively.

12.5 Conclusions

Tackling the nature of science entails *reflection*. When students reflect upon their understanding of science and can relate their ideas to examples of (historic) scientists, they will be able to build an elaborate understanding of the diversity and complexity of science and the processes involved in acquiring scientific knowledge.

Philosophical dialogue can be one of the techniques used to enhance *reflection*. This technique that is more often used in *philosophy* classes can have its own successes in teaching science. It may be particularly relevant to overcome science teachers' caution to address issues with multiple possible answers and different relevant perspectives.

However, nature of science education cannot only be reduced to facilitating dialogues. We must take into account what is known as the 'constructivist mirage'. This implies students are themselves not able to build a complex understanding of science by mere dialogue; students cannot discover in hours what scientists have been working on for ages. The dialogue rather acts like a *reflection* instrument, allowing students to reflect and ponder upon the issues arising in the classroom. Therefore, the use of good stimuli, contexts or examples necessary to start the *discussion* remains a crucial aspect of nature of science education. This makes *philosophical dialogue* an interesting, complementary approach to teach about any of the aspects of NOS.

References

Brecht, B. (1986). *Life of Galileo*. Methuen Drama.

Chakravartty, A. (2011). Scientific Realism. *The Stanford encyclopedia of philosophy* https://plato.stanford.edu/entries/scientific-realism/

Clough, M. (1997). Strategies and activities for initiating and maintaining pressure on students' naive views concerning the nature of science. *Interchange, 28*(2–3), 191–204.

Clough, M. P. (2006). Learners' responses to the demands of conceptual change: Considerations for effective nature of science instruction. *Science & Education, 15*(5), 463–494.

de Schrijver, J. (2016). Daring visitors to think about the nature of science in botanic gardens. *Botanic Gardens Conservation International, 13*(1), 6–8.

de Schrijver, J., Tamassia, L, Van de Keere, K., Vervaet, S. & Cornelissen, E. (2015). Reflecting about the nature of science through philosophical dialogue. EAPRIL Proceedings (2).

Donnelly, J. (1999). Interpreting differences: The educational aims of teachers of science and history, and their implications. *Journal of Curriculum Studies, 31*(1), 17–41.

Donnelly, J. (2004). Humanizing science education. *Science Education, 88*(5), 762–784.

Dunlop, L. (2012). P4C in secondary science. In L. Lewis & N. Chandley (Eds.), *Philosophy for children through the secondary curriculum*. London: Continuum.

Dunlop, L., Humes, G., Clarke, L., & Martin, V. M. (2011). Developing communities of inquiry: Dealing with social and ethical issues in science at key stage 3. (Report). *School Science Review, 93*(342), 113–120.

Duschl, R., & Osborne, J. (2002). Supporting and promoting argumentation discourse in science education. *Studies in Science Education, 38*(1), 39–72. https://doi.org/10.1080/03057260208560187.

Fisher, R. (2007). Dancing minds: The use of Socratic and Menippean dialogue in philosophical enquiry. *Gifted Education International, 22*(2–3), 148–159.

Floridi, L. (2013). What is a philosophical question? *Metaphilosophy, 44*(3), 195–221. https://doi.org/10.1111/meta.12035.

Gardner, S. (1996). Inquiry is no mere conversation *Critical & Creative*. *Thinking, 16*(2), 41–49.

Gazzard, A. (1993). Thinking skills in science and philosophy for children. *Thinking, 7*(3), 32–41.

Gorard, S., Siddiqui, N., & Huat See, B. (2015). *Philosophy for children: Evaluation report and executive summary*. London: Education Endowment Foundation.

Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth graders' views of nature of science. *Journal of Research in Science Teaching, 39*(7), 551–578.

Lederman, N. (2006). Research on nature of science: Reflections on the past, anticipations of the future. *Asia-Pacific Forum on Science Learning and Teaching, 7*(1), 1–11.

Levinson, R., & Turner, S. A. (2001). *Valuable lessons: Engaging with the social context of science in schools: Recommendations and summary of research findings*. London: The Wellcome Trust.

Levinson, R., Hand, M., & Amos, R. (2012). What constitutes high-quality discussion in science? Research from the perspectives on science course. *School Science Review, 93*(344), 114–120.

Lipman, M. (1977). *Harry Stottlemeier's discovery* (Rev. ed.). Upper Montclair: Institute for the Advancement of Philosophy for Children, Montclair State College.

Lipman, M. (2003). *Thinking in education* (2nd ed.). New York: Cambridge University Press.

McComas, W. F. (2015). The nature of science & the next generation of biology education. *The American Biology Teacher, 77*(7), 485–491.

McComas, W. F., & Kampourakis, K. (2015). Using the history of biology, chemistry, geology, and physics to illustrate general aspects of nature of science. *Review of Science, Mathematics and ICT Education, 9*(1), 47–76.

Miller, J. (1998). The measurement of civic scientific literacy. *Public Understanding of Science, 7*(3), 203–223.

Osborne, J. F. (1996). Beyond constructivism. *Science Education, 80*(1), 53–82.

Osborne, J., & Dillon, J. (2010). *Good practice in science teaching: What research has to say* (2nd ed.). Maidenhead/New York: Open University Press.

Palsson, H., Sigurdardottir, B., & Nelson, Y. (1999). *Participation in a "Community of Inquiry" nourishes participants perspective – Talking capacity: A report of a two year empirical study*. Akureyri: University of Akureyri.

Ratcliffe, M. (2007). Values in the science classroom – The 'enacted' curriculum. In D. Corrigan, J. Dillon, & R. Gunstone (Eds.), *The re-emergence of values in science education*. Rotterdam: Sense Publishers.

Sprod, T. (1998). "I can change your opinion on that": Social constructivist whole class discussions and their effect on scientific reasoning. *Research in Science Education, 28*(4), 463–480. https://doi.org/10.1007/BF02461510.

Sprod, T. (2001). Building scientific thinking via philosophical discussion. *Teaching Thinking,* (Autumn), 14–18.

Sprod, T. (2011). *Discussions in science*. Victoria: ACER.

Thiessen, V. (2009). *Einstein's gift*. Toronto: Playwrights Canada Press.

Worley, P. (2016). Ariadne's Clew Absence and presence in the facilitation of philosophical conversations. *Journal of Philosophy in Schools, 3*(2), 51–70.

Chapter 13

Preparing Science Teachers to Overcome Common Obstacles and Teach Nature of Science

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13.1 Current State of NOS Teaching and Learning

Calls for school science to promote among students a more accurate understanding of the nature of science (NOS) have a long history, beginning as far back as at least the mid-nineteenth century (Matthews 2012). Beginning with *Project 2061* (AAAS 1989), most science education reform documents (AAAS 1993, 2001; McComas et al. 2009; McComas and Olson 1998; Olson 2018; NRC 1996; NGSS Lead States 2013) have emphasized the crucial role that NOS understanding plays in scientific literacy (Hodson 2009). The emphasis on promoting accurate NOS understanding is well justified because of the role such understanding plays in:

- Considering, understanding, and accepting many science ideas such as biological evolution (Clough 1994; Dagher and Bou Jaoude 2005; Rudolph and Stewart 1998), the law of pendulum motion (Matthews 2014), and global climate change (Herman 2015; Clough and Herman 2017), to name just a few.
- Improving attitudes toward science, science careers, and science classes (Arya and Maul 2012; Eccles 2005; Hong and Lin-Siegler 2012; Tobias 1990).
- More informed socioscientific decision-making (Allchin 2011; Clough and Herman 2017; Mitchell 2009; Rudolph 2007; Zeidler et al. 2013).

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_13

Despite the long-standing consensus regarding the importance of accurate NOS teaching and learning, the most recent survey of NOS in science teacher education programs in the United States (Backhus and Thompson 2006) determined that "at most perhaps 6% of preservice 9-12 science teachers will have taken [a NOS course] as a requirement." However, because NOS issues are inextricably linked to science content and how science is taught, science teachers convey the NOS regardless of their intent (Clough and Olson 2004). Science instruction and curriculum materials that merely present science content without accurately addressing how such knowledge was developed and came to be accepted, typical media portrayals of science and scientists, cookbook laboratory experiences, and standard laboratory reports all contribute to promoting and supporting NOS misconceptions (Clough 2006; Hodson 2009). Altogether, science is presented in a sanitized way that results in a plethora of misconceptions (Clough 2017), some which include wrongly thinking that (a) well-conducted science research follows a rigid scientific method; (b) scientists should and can be objective in their work; (c) scientific ideas arise directly from data and are supported unambiguously by data; (d) science, when well done, produces absolute truth while knowledge falling short of that status is unreliable; and (e) anomalies demand rejection of science ideas.

13.2 Accurately and Effectively Teaching the NOS

Highly effective NOS instruction shares the same fundamental principles as effective science content instruction. First, teachers must accurately understand the NOS. Second, NOS instruction should be purposely planned and implemented consistently in science instruction. While teachers who effectively teach the NOS seize opportunities that arise unexpectedly during instruction (Herman et al. 2013a), they see NOS learning as a cognitive outcome and also overtly plan how to achieve it. This is no different than overtly determining what science content students should learn, the depth that they should learn it, and planning instruction to meet those objectives. Third, effective NOS instruction demands that teachers overtly draw students' attention to targeted NOS issues and ideas, and do so in a manner that mentally engages students in wrestling with those ideas (Abd-El-Khalick and Lederman 2000; Khishfe and Abd-El-Khalick 2002; Khishfe and Lederman 2006). This, of course, is the case when teaching any science content. For instance, effectively teaching about pendulum motion demands that teachers purposely draw students' attention to key features and factors of pendulum motion in a way that has students think about, wrestle with, and confront their misconceptions in order to come to an accurate and deep understanding of the law of pendulum motion. Fourth, effective NOS instruction occurs in a variety of contexts ranging from decontextualized (devoid of science content), moderately contextualized (associated with science content instruction, but with missing or trivial links to the authentic work and/or words of scientists), to highly contextualized (using the work and words of authentic scientists) with significant scaffolding back and forth between those contexts

(Clough 2006, 2017; Bell et al. 2016). Fifth, particular instructional settings present important opportunities for addressing NOS. For example, Allchin (2011), Herman (2015), Hodson (2009), Khishfe (2014), and Sadler et al. (2004) emphasize the importance of addressing the NOS when investigating socioscientific issues. The empirical work of Herman et al. (2013a) provides evidence showing that effective NOS instruction is significantly aided when teachers implement more general reforms-based science teaching practices (GRBSTPs) such as teaching science through inquiry, requiring extensive student decision-making, and asking questions that assist students in meaning-making. They write:

> In summary, implementing inquiry laboratories and other activities that require student decision-making appear to be the GRBSTPs most important for *creating opportunities* for accurate NOS instruction. Asking thought-provoking extended answer questions and playing off students' ideas in ways that scaffold them to desired understandings appear to be the most important GRBSTPs for *seizing on opportunities* to effectively teach the NOS. Implementing inquiry experiences and other activities that require considerable student decision-making and teachers' proficiency at asking highly effective questions together are important "tools" for NOS implementation efforts whether purposely planned for or arising unexpectedly in the act of teaching a lesson. These tools also make accurately and effectively teaching the NOS a far more natural part of everyday instruction. (Herman et al. 2013a, p. 1094)

Finally, students' NOS understanding must be accurately assessed in a variety of ways (e.g., homework, teacher-developed assessments, and high-stakes exams), for as Dall' Alba et al. (1993) and many others note, "assessment gives clear messages to students about what is important in the subject" (p. 633).

13.3 Obstacles That Interfere with Effective NOS Instruction

Despite science education reform documents calling for accurate NOS instruction (McComas and Olson 1998; McComas and Nouri 2016; Olson 2018), science teachers who want to accurately and effectively teach the NOS often encounter many substantial obstacles that interfere with their efforts. These obstacles derive from sources outside and within the schooling system, and together they make inaccurate NOS instruction or, at the very least, inattention to accurate NOS instruction far safer and easier. Over two decades ago, Lakin and Wellington (1994) wrote that accurate NOS instruction appears to be contrary to "expectations held of science and science teaching in schools, not only by teachers and pupils but also those perceived as being held by parents and society" (p. 186), a situation that continues unabated (Abd-El-Khalick et al. 1998; Bell et al. 2000; Clough and Olson 2012; Herman et al. 2019; Höttecke and Silva 2011; Lederman 1999; Schwartz and Lederman 2002). Extensive NOS research literature documents many impediments to effective NOS instruction including the following:

- Inaccurate NOS understanding held by students, teachers, parents, and policymakers along with inaccurate NOS portrayals by media, science textbooks,

curriculum materials, and science assessments coalesces in a manner that calls into question the more accurate NOS conceptions held by some science teachers and their efforts to convey those accurate ideas to students (Abd-El-Khalick et al. 1998; Bell et al. 2000; Henke and Höttecke 2014; Herman et al. 2017b; Lakin and Wellington 1994; Schwartz and Lederman 2002).
- Lack of support among science teacher colleagues for accurately portraying the NOS in science instruction (Abd-El-Khalick et al. 1998; Bell et al. 2000; Clough and Olson 2012; Herman et al. 2019; King 1991; Lederman 1999).
- Pressure from administrators and science teaching colleagues to enact precisely the same science curriculum and outcomes that misportray the NOS (Clough and Olson 2012; Herman et al. 2019), focus primarily on recall of science content (Anderson 2002; Bell et al. 2000; Duschl and Wright 1989; Hodson 1993), and other constraints that interfere with efforts to teach science through and as inquiry (McGinnis et al. 2004).
- Concerns regarding high stakes testing that is at odds with reform efforts and either ignore or inaccurately assess NOS understanding (Allchin 2011; Aydeniz and Southerland 2012).
- Insufficient time for planning and implementing accurate NOS instruction (Bell et al. 2000; Lakin and Wellington 1994; Abd-El-Khalick et al. 1998; Clough and Olson 2012; Lederman 2007).
- Lack of support for general reforms-based science teaching practices that would create opportunities to accurately address the NOS in everyday instruction (Herman et al. 2013a; Herman et al. 2019; McGinnis et al. 2004).
- Classroom management concerns associated with implementing accurate NOS instruction because such instruction may appear contrary to what students expect in science classes (Abd-El-Khalick et al. 1998; Brickhouse and Bodner 1992; Duschl and Wright 1989; Hodson 1993; Lantz and Kass 1987).

Understanding why and how some science teachers do accurately and effectively teach the NOS in the face of these formidable obstacles is crucial for preservice and in-service science teacher education efforts directed toward accurate NOS instruction.

13.4 Characteristics and Actions of Teachers Who Overcome NOS Instruction Obstacles

Efforts to promote research-based teaching practices that are aligned with desired ends appearing in science education reform documents have largely been unsuccessful (Banilower et al. 2013; Crawford 2007). This is the case with NOS instruction as well as general reforms-based science teaching practices. Even when teachers understand the complexities of learning and effectively teaching science, research-based pedagogical decision-making and practices require time and effort to master. But the lack of research-based science teaching practices appearing in schools also reflects the complexities in effectively teaching science *and* fierce institutional constraints that promote the status quo. Institutional expectations for teachers to address precisely the same content, provide common instructional experiences, and implement the same assessments all conspire against reforms-based practices including accurate and effective NOS instruction (Ihrig et al. 2014; McGinnis et al. 2004). Schools are long-established social institutions that often provide little support and even less patience for teachers who deviate from familiar traditional practices. Studies reporting the paucity of accurate and effective NOS instruction occurring in science classrooms, despite concerted efforts to promote such instruction, have extensively documented clear impediments to NOS instruction like those noted in the prior section.

Recent NOS research has focused on science teachers who accurately and effectively teach the NOS to determine how they persevere, navigate, and overcome those institutional constraints (e.g., Herman et al. 2019). Such research has determined that science teachers who triumph in their efforts to accurately and effectively teach the NOS exhibit the following:

- *They deeply understand what effective NOS pedagogy entails and are aware of how complex and difficult implementing it can be.* Fully grasping the fundamental principles of effective NOS instruction described earlier in this chapter, teachers who effectively persevere over institutional constraints do not give in to the intuitive, yet incorrect, approach that students' NOS understanding will significantly improve merely through occasional decontextualized NOS activities and/or implicit NOS learning experiences.
- *They possess fervent practical and transcendental rationales for NOS teaching and learning.* Merely valuing the NOS as a learning outcome for its own sake is insufficient for actually teaching it, particularly in the face of real or perceived institutional constraints. Valuing NOS for improving science content learning and improving attitudes toward science and scientists are also important, but even those ends are often insufficient. Herman et al. (2017a) report that high and medium NOS instruction teachers in their study saw accurate NOS instruction as nonnegotiable because of "the value of NOS for citizenship and socioscientific decision-making—goals that transcend their course, high-stakes exams, and other more proximal concerns of schooling" (p. 179).
- *They connect with other teachers who seek to accurately and effectively teach the NOS.* Herman et al. (2019) found that teachers who sought and worked with other teachers who were committed to NOS instruction more extensively valued, understood, and implemented accurate and effective NOS instruction. These support networks entailed contacts with like-minded teachers, often from other schools or school districts, sometimes at great distances.
- *They do not see themselves as having to always follow the lead of their colleagues or take orders from their administrators.* Herman et al. (2019) report that high NOS implementers in their study who faced institutional constraints "worked in a self-directed manner and were not 'owned by' or 'subject to' the constraints found in their school environments" (p. 205). Drawing from the work

of Drago-Severson (2007) and Kegan (1994), they found that these teachers were more able to "balance their concerns in juxtaposition with the concerns of others, and engage in more sophisticated forms of socialization such as critically and objectively analyzing and responding to what is requested of them in conjunction with their own values" (p. 193).

- *They are politically savvy.* Successfully navigating institutional constraints requires accurately assessing social situations and perhaps making decisions not to draw others' attention to NOS instruction efforts. Not talking to colleagues and administrators about their NOS instruction, overtly making statements and providing examples that illustrate instances where curricular expectations are being followed, deftly altering lessons when a colleague or an administrator enters the room so that overt NOS instruction is not observed, and other moves that deflect awareness of the NOS instruction taking place are just a few examples of savvy decisions teachers make in their efforts to accurately and effectively teach the NOS.
- *They leave a school where accurate and effective NOS instruction is not possible.* Some school environments are so filled with constraints and treachery that putting into place reforms-based science teaching practices, such as accurate and effective NOS instruction, is not possible. In these settings, archaic expectations may be imposed on teachers committed to effective science teaching to the extent that such teachers may quit or be forced out of the profession (Ihrig et al. 2014; McGinnis et al. 2004; Veenman 1984). Research documents that teachers who remain in such hostile environments for 2 years became very traditional in their teaching practices while those who leave and find more flexible schools are more likely to persevere in their efforts to put into place research-based teaching practices aligned with science education reform documents (Ihrig et al. 2014).

For teachers who persevere against institutional constraints, teaching is not merely a job. They truly have students' and society's best interests at heart, are knowledgeable and thoughtful, are highly reflective, and will take risks to ensure students receive the very best *education*.

13.5 Preparing Teachers to Navigate Constraints That Work Against NOS Teaching

Because accurate NOS instruction is not the status quo in schools, preservice teacher education programs and professional development efforts must prepare teachers to teach the NOS in the context of the institutional constraints they will likely face. Beginning science teachers are particularly vulnerable to institutional constraints because (a) they have yet to competently put into place the research-based practices they have only recently learned, often struggle with classroom management, and therefore are more easily criticized and pushed into archaic practices; (b) they are new to the school where they teach and are thus unaware of how well their efforts at reforms-based practices will be received and where political landmines exist; and (c) in many school districts, teachers in their first years of teaching can be dismissed with no explanation.

For nearly 20 years, the second and third authors have followed graduates from a secondary science teacher education program they created and directed at a prior university in the Midwestern United States—one with a strong NOS component—to better understand how to best prepare science teachers who understand and implement research-based pedagogical decision-making aligned with science education reform documents, including NOS instruction. Based on this and our more recently published research focusing on successful NOS instruction implementation efforts (Clough and Olson 2012; Herman and Clough 2016; Herman et al. 2013a, b; Herman et al. 2017a; Herman et al. 2019), we recommend the following strategies for preparing teachers who will accurately and effectively teach the NOS despite fierce institutional constraints. These recommendations for navigating and overcoming potential institutional constraints are explicitly addressed in our efforts with preservice teachers, and they certainly apply to assisting experienced science teachers as well.

- *Significant attention should be devoted to exploring compelling rationales for schooling, science content instruction, and NOS instruction.* Several intuitive and commonly stated primary purposes for schooling (e.g., recent emphasis on STEM careers and economic utility) are philosophically unsound, and they do not provide compelling reasons for most students to learn science or for science teachers to devote extensive effort to teach science well. Clough (2008) noted that:

> without commitment to the philosophical and moral aspects of schooling, research-based teaching becomes mechanical and detached from children. Without attention to the sacred nature of teaching, teaching becomes simply a job. (p. 2)

We have teachers read and seriously consider the work of John Dewey (1902), Neil Postman (1995), and others in order to develop a fervent rationale for schooling, teaching science, and NOS instruction. Throughout our science teacher education program, we repeatedly return to more noble and transcendental reasons for each of these, repeatedly emphasizing the differences between education and training. We push our preservice teachers to deeply understand the shortcomings of intuitive and commonly provided rationales for schooling, and develop an internal ethical stance and sense of responsibility for accurately teaching the NOS as part of a noble and meaningful science *education*.

- *NOS content and pedagogical understanding must be promoted at a deep level and revisited throughout a science teacher education program.* In order to overcome barriers to NOS instruction, science teachers must understand the contextual nature of NOS ideas in order to "see" NOS ideas in the context of everyday science content instruction and socioscientific issues (e.g., see Clough and Herman (2017) for the important role NOS instruction plays in global climate change education). Teachers must be taught how to restructure science activities to create opportunities for teaching the NOS and conveying its importance in those contexts. Deep NOS content and pedagogical understanding is also crucial for accurate NOS instruction self-reflection which should occur at several stages in a science teacher education program. Obviously, addressing all this in a single science methods course is problematic in light of all else that must be accomplished in preparing science teachers. Our secondary science teacher preparation program consisted of a series of three required science methods courses (four for those completing the graduate licensure program) and a required NOS course that students completed early in the program. This provided the time necessary to promote NOS content understanding and NOS pedagogy understanding that was repeatedly revisited in further science methods courses.

- *Overtly teach how to navigate potential, but undetected, barriers to NOS instruction.* Until completing their probationary period or achieving certainty that accurate NOS instruction is supported in their school district, we urge preservice teachers to tread carefully when talking about or doing anything that might draw others' attention to their NOS instruction efforts. For instance, we teach preservice teachers how to communicate with clear statements and provide examples to assigned mentors, colleagues, and administrators that convey curricular and pedagogical expectations are being followed, that imply what they are doing is aligned with what others teaching the same subject are doing, how to immediately alter lessons if a colleague or an administrator enters the room so that expected content instruction is observed, and other moves that deflect awareness of the NOS instruction taking place.
- *Encourage preservice teachers to seek a culture of collegiality and support among colleagues who implement accurate NOS instruction.* Our teacher education program purposely used a cohort model approach so that preservice teachers would more likely form strong bonds with one another. We emphasize the need for preservice teachers to stay in contact with one another and us after graduation, and also seek out other like-minded individuals who can support their NOS instruction efforts. Undeniably, some science teaching colleagues in a school or district may support accurate NOS instruction and general reforms-based science teaching practices. Thus, we teach preservice teachers to listen carefully to their colleagues and ask for their activities and other curricular materials to be *certain* they have identified a colleague who will support their NOS and general reforms-based instruction efforts. This strategy also permits them to learn what colleagues are doing and use strategies noted in the prior bullet point.
- *Draw preservice teachers' attention to the characteristics and attributes of teachers who accurately and effectively teach the NOS.* This recommendation is important for convincing teachers that the NOS can and should be accurately taught despite lack of support or outright constraints. Examples of teachers successfully incorporating NOS instruction are important, as well as research addressing the characteristics and attitudes of teachers who accomplish effective NOS instruction (described in the previous section of this chapter). We emphasize the aspects of teaching that are under teachers' control, even if they must be

clever in their efforts. This includes providing examples of program graduates' struggles and strategies they used to navigate institutional constraints. We emphasize that teachers who truly care about students will not permit institutional constraints to dictate what they do and cave into the status quo. This does not mean preparing teachers who ignore very real limits to what they can do, but who listen to, acknowledge, and effectively navigate others' perspectives and expectations without settling for common archaic practices.

- *Remind preservice teachers of the need to leave a school where reforms-based practices, including accurate and effective NOS instruction, are unlikely to be tolerated.* Research following graduates of our previous teacher education program during their first 2 years (Ihrig et al. 2014) determined that most taught in schools where both accurate NOS instruction and general reforms-based science teaching practices were ridiculed in favor of archaic and standardized practices. None of the teachers studied were in a school where a mentor or colleague was particularly knowledgeable of research-based pedagogical practices aligned with reform documents. Beginning teachers often faced hostile environments (e.g., expectations of conformity to trivial worksheets, cookbook activities, multiple-choice assessments; mentors who reported to principals that beginning teachers were deviating from what others were doing; and administrators who threatened dismissal for not teaching in traditional ways), resulting in a deterioration of their teaching practices aligned with accurate NOS instruction and general reforms-based science teaching practices. If teachers in such settings moved after their first year to a more supportive environment, their practices recovered by the end of the second year, but their distrust of colleagues and administrators remained. However, if they remained in such hostile environments, their practices continued to decline and they were far less likely to be aware that their practices were ineffective.

Accurate and effective NOS instruction and the recommendations above should be revisited throughout a teacher education program. Consistent modeling of accurate and effective NOS instruction along with assignments that are more fully developed and extended through a teacher education program are important so that by the end of the program, habits of mind and action are developed. Assignments in each science education course should be intellectually demanding and coupled with very high expectations and support to promote cohort cooperation and interdependence. During the student teaching semester, require a formal meeting one evening each week to ensure students have the support of one another and program faculty in efforts to keep students thinking about the noble ends of science education and what is required to reach those ends. We work hard to create relationships with preservice teachers that extend beyond their graduation and encourage them to contact us when facing constraints in their first years of teaching. The recommendations above assist students in surviving and more likely thriving in their first years of teaching, thus resulting in NOS teaching practices 2–5 years later (Herman et al. 2013b) exceeding that generally reported in the literature.

References

Abd-El-Khalick, F., & Lederman, N. G. (2000). The influence of history of science courses on students' views of nature of science. *Journal of Research in Science Teaching, 37*(10), 1057–1095.

Abd-El-Khalick, F., Bell, R. L., & Lederman, N. G. (1998). The nature of science and instructional practice: Making the unnatural natural. *Science Education, 82*(4), 417–436.

Allchin, D. (2011). Evaluating knowledge of the nature of (whole) science. *Science Education, 95*(3), 518–542.

American Association for the Advancement of Science. (1989). *Project 2061: Science for all Americans*. Washington, DC: Author.

American Association for the Advancement of Science. (1993). *Benchmarks for science literacy*. New York: Oxford University Press.

American Association for the Advancement of Science. (2001). *Atlas of science literacy*. Washington, DC, Author.

Anderson, R. (2002). Reforming science teaching: What research says about inquiry. *Journal of Science Teacher Education., 13*(1), 1–12.

Arya, D. J., & Maul, A. (2012). The role of the scientific discovery narrative in middle school science education: An experimental study. *Journal of Educational Psychology, 104*(4), 1022–1032.

Aydeniz, M., & Southerland, S. A. (2012). A national survey of middle and high school science teachers' responses to standardized testing: Is science being devalued in schools? *Journal of Science Teacher Education, 23*(3), 233–257.

Backhus, D. A., & Thompson, K. W. (2006). Addressing the nature of science in preservice science teacher preparation programs: Science educator perceptions. *Journal of Science Teacher Education, 17*(1), 65–81.

Banilower, E. R., Smith, P. S., Weiss, I. R., Malzahn, K. A., Campbell, K. M., & Weis, A. M. (2013). *Report of the 2012 national survey of science and mathematics education*. Chapel Hill: Horizon Research.

Bell, R. L., Lederman, N. G., & Abd-El-Khalick, F. (2000). Developing and acting upon one's conception of science: A follow-up study. *Journal of Research in Science Teaching, 37*(6), 563–581.

Bell, R. L., Mulvey, B. K., & Maeng, J. L. (2016). Outcomes of nature of science instruction along a context continuum: Preservice secondary science teachers' conceptions and instructional intentions. *International Journal of Science Education, 38*(3), 493–520.

Brickhouse, N. W., & Bodner, G. M. (1992). The beginning science teacher: Narratives of convictions and constraints. *Journal of Research in Science Teaching, 29*(5), 471–488.

Clough, M. P. (1994). Diminish students' resistance to evolution education. *The American Biology Teacher, 56*(7), 409–415.

Clough, M. P. (2006). Learners' responses to the demands of conceptual change: Considerations for effective nature of science instruction. *Science & Education, 15*(5), 463–494.

Clough, M. P. (2008). Teaching as a sacred activity. *Iowa Science Teachers Journal*, Editorial, 35(1): 2. https://www.scienceiniowa.org/ists-journal

Clough, M. P. (2017). Chapter 3: History and nature of science in science education. In K. Taber & B. Akpan (Eds.), *Science education: An international course companion* (pp. 39–51). Rotterdam: Sense Publishers.

Clough, M. P., & Herman, B. C. (2017). Chapter 2: The role of history and nature of science in climate change teaching and learning. In D. P. Shepardson, A. Roychoudhury, & A. S. Hirsch (Eds.), *Teaching and learning about climate change* (pp. 15–28). New York: Routledge.

Clough, M. P., & Olson, J. K. (2004). The nature of science: Always part of the science story. *The Science Teacher, 71*(9), 28–31.

Clough, M. P., & Olson, J. K. (2012). Chapter 12: Impact of a nature of science and science education course on teachers' nature of science classroom practices. In M. S. Khine (Ed.), *Advances in nature of science research: Concepts and methodologies*. Dordrecht: Springer.

Crawford, B. A. (2007). Learning to teach science as inquiry in the rough and tumble of practice. *Journal of Research in Science Teaching, 44*(4), 613–642.

Dagher, Z. R., & Bou Jaoude, S. (2005). Students' perceptions of the nature of evolutionary theory. *Science Education, 89*(3), 378–391.

Dall' Alba, G., et al. (1993). Textbook treatments and students' understanding of acceleration. *Journal of Research in Science Teaching, 30*(7), 621–645.

Dewey, J. (1902). *The child and the curriculum*. Chicago: University of Chicago Press.

Drago-Severson, E. (2007). Helping teachers learn: Principles as professional development leaders. *Teachers College Record, 109*(1), 70–125.

Duschl, R. A., & Wright, E. (1989). A case study of high school teachers' decision making models for planning and teaching science. *Journal of Research in Science Teaching, 26*(6), 467–501.

Eccles, J. (2005). *Why women shy away from careers in science and math.* U of M News Service, Available at http://www.umich.edu/news/index.html?Releases/2005/Apr05/r041405, Retrieved January 23, 2010.

Henke, & Höttecke. (2014). Physics teachers' challenges in using history and philosophy of science in teaching. *Science & Education, 24*(4), 349–385.

Herman, B. C. (2015). The influence of global warming science views and sociocultural factors on willingness to mitigate global warming. *Science Education*, 99(1), 1–38.

Herman, B. C., & Clough, M. P. (2016). Teachers' longitudinal NOS understanding after having completed a science teacher education program. *International Journal of Science and Mathematics Education, 14*(1), 207–227.

Herman, B. C., Clough, M. P., & Olson, J. K. (2013a). Association between experienced teachers' NOS implementation and reform-based practices. *Journal of Science Teacher Education, 24*(7), 1077–1102.

Herman, B. C., Clough, M. P., & Olson, J. K. (2013b). Teachers' NOS implementation practices two to five years after having completed an intensive science education program. *Science Education, 97*(2), 271–309.

Herman, B. C., Clough, M. P., & Olson, J. K. (2017a). Pedagogical reflections by secondary science teachers at different NOS implementation levels. *Research in Science Education, 47*(1), 161–184.

Herman, B. C., Feldman, A., & Vernaza-Hernandez, V. (2017b). Florida and Puerto Rico secondary science teachers' climate change conceptions and teaching practices. *International Journal of Science and Mathematics Education., 15*(3), 451–471.

Herman, B. C., Olson, J. K., & Clough, M. P. (2019). The role of informal support networks in teaching the nature of science. *Research in Science Education, 49*(1), 191–218.

Hodson, D. (1993). Philosophic stance of secondary school science teachers, curriculum experiences, and children's understanding of science: Some preliminary findings. *Interchange, 24*(1–2), 41–52.

Hodson, D. (2009). *Teaching and learning about science: Language, theories, methods, history, traditions and values*. Rotterdam: Sense Publishers.

Hong, H., & Lin-Siegler, X. (2012). How learning about scientists' struggles influences students' interest and learning in physics. *Journal of Educational Psychology, 104*(2), 469–484.

Höttecke, D., & Silva, C. C. (2011). Why implementing history and philosophy in school science education is a challenge: An analysis of obstacles. *Science & Education, 20*(3–4), 293–316.

Ihrig, L., Clough, M. P. & Olson, J. K. (2014). *Effects of formal and informal support relationships on experiences and practices of first-year science teachers.* Paper presented at the National Association for Research in Science Teaching International Conference, Pittsburgh, PA, March 30–April 2.

Kegan, R. (1994). *In over our heads: The mental demands of modern life*. Cambridge: Harvard University Press.

Khishfe, R. (2014). Explicit nature of science and argumentation instruction in the context of socioscientific issues: An effect on student learning and transfer. *International Journal of Science Education, 36*(5–6), 974–1016.

Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry oriented instruction on sixth graders views of the nature of science. *Journal of Research in Science Teaching, 30*(7), 551–578.

Khishfe, R., & Lederman, N. (2006). Teaching nature of science within a controversial topic: Integrated versus nonintegrated. *Journal of Research in Science Teaching, 43*(4), 395–418.

King, B. (1991). Beginning teachers' knowledge of and attitude toward history and philosophy of science. *Science Education, 75*(1), 135–141.

Lakin, S., & Wellington, J. (1994). Who will teach the nature of science? Teachers' views of science and their implications for science education. *International Journal of Science Education, 16*(2), 175–190.

Lantz, O., & Kass, H. (1987). Chemistry teachers' functional paradigms. *Science Education, 71*, 117–134.

Lederman, N. G. (1999). Teachers' understanding of the nature of science and classroom practice: Factors that facilitate or impede the relationship. *Journal of Research in Science Teaching, 36*(8), 916–929.

Lederman, N. G. (2007). Nature of science: Past, present, and future. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 831–880). Mahwah: Erlbaum.

Matthews, M. (2012). Chapter 1: Changing the focus: From nature of science (NOS) to features of science (FOS). In M. S. Khine (Ed.), *Advances in nature of science research: Concepts and methodologies*. Dordrecht: Springer.

Matthews, M. (Ed.). (2014). *International handbook of research in history and philosophy for science and mathematics education*. Dordrecht: Springer.

McComas, W. F., & Nouri, N. J. (2016). The nature of science and the next generation science standards: Analysis and critique. *Journal of Science Teacher Education, 27*(5), 555–576.

McComas, W. F., & Olson, J. K. (1998). Chapter 2: The nature of science in international standards documents. In W. F. McComas (Ed.), *The nature of science in science education: Rationales and strategies*. Dordrecht: Kluwer.

McComas, W. F., Lee, C. K. & Sweeney, S. J. (2009). *A critical review of current U.S. State Science Standards with respect to the inclusion of elements of the nature of science.* Paper presented at the annual meeting of the National Association for Research in Science Teaching. Garden Grove, CA (April 17–21).

McGinnis, J. R., Parker, C., & Graeber, A. O. (2004). A cultural perspective of the induction of five reform-minded beginning mathematics and science teachers. *Journal of Research in Science Teaching, 41*(7), 720–747.

Mitchell, S. (2009). *Unsimple truths: Science, complexity, and policy*. Chicago: University of Chicago Press.

National Research Council. (1996). *National Science Education Standards*. Washington, DC: National Academies Press.

NGSS Lead States. (2013). *Next generation science standards: For states, by states*. Washington: DC, National Academies Press.

Olson, J. K. (2018). The Inclusion of the nature of science in nine recent international science education standards documents. *Science & Education, 27*(7-8), 637–660.

Postman, N. (1995). *The end of education: Redefining the value of school*. New York: Vintage Books.

Rudolph, J. L. (2007). An inconvenient truth about science education. *Teachers College Record.* Retrieved September 26, 2007, from http://www.tcrecord.org/content.asp?contentid=13216. ID number 13216.

Rudolph, J. L., & Stewart, J. (1998). Evolution and the nature of science: On the historical discord and its implications for education. *Journal of Research in Science Teaching, 35*(10), 1069–1089.

Sadler, T. D., Chambers, F. W., & Zeidler, D. L. (2004). Student conceptualizations of the nature of science in response to a socio-scientific issue. *International Journal of Science Education, 26*(4), 387–409.

Schwartz, R. S., & Lederman, N. G. (2002). "It's the nature of the beast": The influence of knowledge and intentions on learning and teaching the nature of science. *Journal of Research in Science Teaching, 39*(3), 205–236.

Tobias, S. (1990). *They're not dumb, They're different: Stalking the second tier*. Tucson: Research Corporation.

Veenman, S. (1984). Perceived problems of beginning teachers. *Review of Educational Research, 54*(2), 143–178.

Zeidler, D., Herman, B. C., Ruzek, M., Linder, A., & Lin, S. S. (2013). Cross-cultural epistemological orientations to socioscientific issues. *Journal of Research in Science Teaching, 50*(3), 251–283.

Chapter 14
Perspectives for Teaching About How Science Works

Fred Janssen, Hanna Westbroek, Ilse Landa, Britt van der Ploeg, and Jacqueline Muijlwijk-Koezen

An integrative, perspective-directed, and practical approach to teaching the nature of science is elaborated in this contribution. The approach is *integrative* in the sense that students reflect on general and domain-specific aspects of knowledge development. In order to do this, students contribute to knowledge development using domain-specific *perspectives* that guide them in formulating questions as well as answers and criteria to assess those answers. The approach is *practical* in the sense that three heuristics were developed that offer teachers practical design support for redesigning their regular lessons into integrative, perspective-based lessons.

14.1 Introduction

There is a long-standing tradition that advocates the implementation of nature of science (NOS) aspects in science education (Lederman and Lederman 2014; Hodson 2014; Allchin 2013; Niaz 2011). Roughly two influential visions on the teaching and learning of NOS can be distinguished: a *general aspects* approach and a *domain-specific* approach (Kampourakis 2016; Duschl and Grandy 2013).

The "general aspects" approach suggests that a limited set of NOS aspects that are common to all the natural sciences should be explicitly taught in science education. Examples are "science produces, demands, and relies on empirical evidence" and "scientific knowledge is tentative, durable and self-correcting." Although different versions of the "general aspects" approach exist, some important aspects are

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_14

common in all lists (see Kampourakis 2016 for an overview). Students often have misconceptions about these general aspects of NOS (Lederman and Lederman 2014). To address students' conceptions, teachers are advised to explicitly reflect with students on general NOS aspects, on the basis of both lesson situations (e.g., when students make observations through a microscope, the teacher can emphasize the difference between observation and inference) and historical cases of scientific research (see McComas and Kampourakis 2015 and in this volume as Chapter 30 for many historical cases to illustrate general aspects of NOS).

The domain-specific approach to teaching NOS takes a somewhat different stance. In this approach, students, with support from their teachers, participate in scientific practices such as formulation of research questions, and to the development and critical testing of models and constructing arguments (Duschl and Grandy 2013). The premise is that students, by participating in scientific practices and by reflecting on process and product, develop not only scientific knowledge but also insight in domain-specific aspects of knowledge development. If, for example, students are stimulated to develop particle model explanations for certain properties of substances and to reflect on explanations and process afterwards, they learn not only about specific aspects of particles, such as different types of particles giving rise to different types of bonds, but also about the type of questions that become relevant in the process of searching for a particle explanation, the nature of particle models and their limitations, and what are valid arguments for evaluating such models.

The approach to teaching NOS that we elaborate in this chapter builds on both the general aspects and the domain-specific approach, but differs in three ways: it is an integrative, perspective-directed, and practical approach to teaching NOS. We will briefly discuss each of these three aspects.

Integrative We agree with Kampourakis that both general and domain-specific approaches have valuable elements and that students need to be offered opportunities to gain experiences with both. Kampourakis (2016) proposes that students are first taught a general aspects approach, before they are taught a domain-specific approach. In our approach we integrate both in the opposite order. Students are stimulated to contribute themselves to knowledge development, supported by the teacher. Reflection on the product and the process of knowledge development contributes to insight in the scientific models that are used and developed and in domain-specific ways of thinking. After participating in this type of knowledge development processes in the context of different domains, the teacher can reflect with the students on their experiences and on more general aspects of NOS.

Perspective-Directed There is broad consensus among philosophers of science that knowledge development is directed by more general ideas (Kuipers 2007). Ideas such as "substances consist of particles" and "properties of organisms fulfil a function" are not the outcome of research but rather the starting point. Such ideas direct what are relevant type of questions, which type of models are developed, and what are important criteria for evaluating these models (see, for an overview, Kuipers 2007). Different terms are used to refer to these general ideas, such as paradigms

(Kuhn), research programs (Lakatos), and perspectives (Giere). In our approach we prefer the term "perspective" because it covers the function of the general ideas. A perspective lights up certain aspects of the "real world" and directs the research on those aspects. At the same time a perspective blinds you for other aspects. Therefore, many complex problems ask for a multiperspective approach (Wimsatt 2007). A researcher's background and goals determine to a large extent the perspective or perspectives he or she adopts in the process of knowledge development (Giere 2010b). Philosophers of sciences broadly subscribe the significance of perspectives as epistemic scaffolds. In spite of this, perspectives are rarely elaborated in the domain-specific approach to NOS in science education, as scaffolds for supporting students with knowledge development. Perspective-directed knowledge development is central to our approach. It provides opportunities for students to reflect on possibilities and limitations of perspectives, and subsequently on the nature, the strengths, and the weaknesses of specific domain-specific ways of thinking.

Practical Many proposals for teaching NOS, and especially those that are developed within the domain-specific tradition, are considered unpractical by teachers (Janssen and Van Berkel 2015; Janssen et al. 2013). The reason is that teachers are not provided with tools that enable them within the available time and resources to redesign their regular lessons in a relatively simple way to lessons that support students with contributing to knowledge development, without undermining other important goals such as cover content in time and create work order. This is one of the most important reasons of the lack of impact on practice of ambitious educational change proposals from the domain-specific tradition (Janssen and Van Berkel 2015). To meet the criterion of practicality, we therefore developed practical tools for teachers that enable them to implement our approach to NOS in their regular teaching practice.

In sum, in this chapter we propose a practical and integrative approach to teaching NOS that starts with engaging students in contributing to perspective-directed knowledge development. By reflecting on these experiences, students develop insight in domain-specific ways of thinking. After students have experienced different domain-specific ways of thinking this way, they can reflect with the teacher on general aspects of NOS. For this purpose we reformulated the NOS aspects that McComas (2008) proposes as questions.

This chapter is structured as follows. To illustrate the idea of a perspective and how perspectives function in domain-specific knowledge development processes, we first discuss the historical case of the chemist Pauling and the biologist Burnet. Both wanted to understand how a diversity of antibodies can be produced, but approached the problem from very different perspectives. This led to two different models for explaining the problem of diversity of antibodies. Next, we introduce the practical tools that teachers are offered to redesign their regular lessons into lessons that support students with perspective-directed domain-specific knowledge development, and with reflection on more general aspects of product and process. The type of learning processes that emerge are illustrated with two examples: a functional perspective in biology and a particle perspective in chemistry. Finally, we discuss how teachers can support students with reflecting on their experiences with perspective-based domain specific knowledge development to learn about general aspects of NOS.

14.2 An Illustration of the Role of Perspectives in Knowledge Development

The field of immunology had a period of rather stormy developments in the 1940s and 1950s (Silverstein 2009). One of the central questions at the time related to the mechanism by which the human body produces a variety of structures (antibodies) that are able to specifically recognize other structures (antigens) within the enormous diversity of those antigens found on invading pathogens and particles that might enter the body. Several models were developed to explain this specificity problem. The chemist Linus Pauling and the biologist Frank MacFarlane Burnet each approached the problem from their own scientific field in order to explain the phenomenon. This nicely illustrates the extensive influence of their scientific background on the modeling process.

In 1940, Pauling began his work on the unrevealed mechanism behind the specificity of antibodies from the perspective of his knowledge regarding inter- and intramolecular forces. He asked the question: “what is the simplest suggestible structure for a molecule with the properties observed for antibodies, based on the extensive information now available about inter- and intramolecular forces, and what is the simplest reasonable formation process of such a molecule?” (Pauling 1940, p. 2643). The model he designed came to be known as a direct template model for antibody formation. First the antigen “instructs” that an amino acid chain be formed, and then the protein is folded into the appropriate 3D structure, using the antigen as template. This direct template model was criticized by the biologist Burnet in part because he applied a functional biological perspective to the problem. Burnet argued that Pauling’s model did not explain various aspects of the specificity problem that are functionally important for the survival and reproduction of the organism. Burnet’s models, and those developed by other biologists in that period, “…were devised primarily to account for two sets of phenomena for which the direct template theory seems quite irrelevant. The first is the absence of immunological response to ‘self’ constituents and the related phenomena of immunological tolerance; the second is the evidence that antibody production can continue in the absence of antigen” (Burnet 1957*, p. 68).*

Thus, instead of clarifying the specificity of antibodies by the chemical structure and bonding of the molecules involved, Burnet wanted to explain the functional adaptations of antibody forming. He developed two alternatives. New insights in DNA function and protein synthesis resulted in both models being evaluated as rather unlikely. Burnet finally replaced the instruction-type models with a clonal selection model (Burnet 1957). This clonal model not only fitted neatly with the new insights in DNA and protein synthesis, but it also explained the functional adaptations of the immune response rather well. In Burnet's clonal selection model, the antigen does not "instruct" which antibody needs to be formed, but—analogous to the evolution theory—random cells first are produced with receptors that each can bind only one type of antigen. After binding the antigen (selection), the respective cell is produced rapidly, and its "offspring" will produce the specific antibodies.

This case shows that the chosen perspective not only determines how the research question is formulated, but what type of models are developed and which specific criteria are considered to be important when testing those models. In this case the chemical structure and bonding perspective and the functional biology perspective are complementary. Although Burnet's clonal selection model prevailed, Pauling's underlying molecular key-lock principle of biological specificity has inspired a variety of new research subfields, such as drug design.

14.3 Perspective-Based Knowledge Development in Science Classrooms

In traditional science lessons, students generally do not contribute to knowledge development, and perspectives hardly play a role. Schwab (1962) characterized these types of lessons as "rhetoric of conclusions." Knowledge is provided ready-made and subsequently mastered through practice with solving standard problems. Students do not learn what domain-specific ways of thinking and reasoning are that can be used to develop knowledge. How to convert traditional ready-made science lessons into science-in-the making lessons? For this, we developed practical tools (also referred to as heuristics) that enable teachers to redesign their regular lessons in a cost-effective way into lessons that support students with perspective directed knowledge development and with reflection on the nature of this process and its products (Fig. 14.1).

1. Reverse the usual sequence of lesson parts or lesson segments (reverse-heuristic).
2. Remove certain lesson parts or segments selectively, and offer these to students when needed (selective omission heuristic).
3. Formulate general ideas that underlie the topic and content at hand as questions (reformulation heuristic).

Below we will illustrate and explain these three heuristics by means of a biology lesson for grade 9 students about spiders making a web using the biological functional perspective. In addition, we discuss an example of knowledge development from the chemical particle perspective.

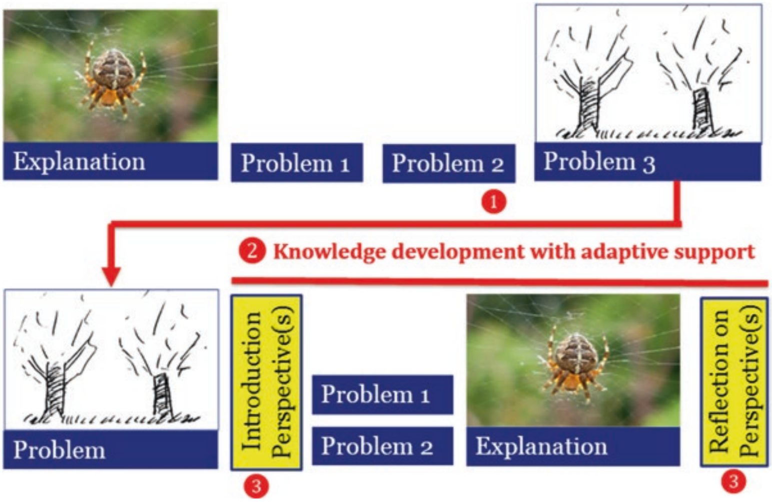


Fig. 14.1 Three heuristics for converting regular science lessons into perspective-based knowledge development. Exemplified for teaching about how spiders make their webs

14.3.1 Perspective-Directed Knowledge Development in Biology Education: Using a Functional Perspective

The regular lesson of the teacher in this case had the typical pattern of many science lessons (Janssen and Van Berkel 2015): First, the teacher explains the new subject matter, after which students work on problems in order to check whether they understood the new theory. In this case the teacher showed his students a video that showed a spider making a web. Next, students worked on a series of relatively easy and more complex problems, such as the following: students were asked how a spider secures that his prey does not fly away again after getting caught in the web (problem 1), and how do spiders tune their web to catch prey? (problem 2). And students were asked to draw a web between two trees and explain how a spider can make such a web (problem 3). Next we show how a teacher can redesign his or her lesson to a lesson that supports perspective-directed knowledge development using the three heuristics.

Reverse Heuristic In traditional lessons, knowledge is presented ready-made, whereas in perspective-based teaching, lessons start—similar to scientific research—with the formulation of the problem. First the teacher chooses a problem that covers the learning goals as much as possible and places the problem at the start of the lesson. The problem does not need to be the same problem as the original research problem that led to the knowledge development in the first place. It is important, however, that both the perspective and the knowledge that are taught in the particular lesson are needed for solving the problem. The teacher might want to adapt the problem to make it more suitable, relevant, and motivating for the students (see Janssen and Van Berkel (2015) for additional guidelines for problem formulation and problem introduction). In this particular case, the teacher chooses the problem "draw a spider web between the trees and explain how a spider can make such a web" (problem 3). This is a complex problem. Students will need support with solving it.

Selective-Omission Heuristic Lesson parts or segments can be used as an adaptive support for students. This implies that everything that students are offered in a regular lesson, such as "explanation of new subject matter" or "practice applying the new knowledge," can be considered support for solving the complex problem that is introduced at the start of the lesson. All these normal lesson segments are omitted and only offered to students when they indicate that they need the lesson segment. In this case, the teacher, for example, let his students think about the spider web problem for the first 10 minutes. If they got stuck, they were offered problem 1. Problem 1 contained a hint for the solution (a spider should at least make sure that a prey does not fly away again). After another 10 minutes, the teacher offered the video that shows a spider making a web and students were given the assignment to evaluate and to adjust and/or complete their theory of how a spider makes a web, using the information in the video.

Reformulation Heuristic The regular lesson is now redesigned into a lesson that supports students with contributing to knowledge development. A perspective that is fundamental to the subject matter at hand and that directs this process is still missing. An important idea that is fundamental to many properties of organisms is the idea of functionality: a property seems to be adjusted in such a way that it fulfils one or more functions in a certain environment with the least possible disadvantages for the survival and reproduction of the organism. This idea is well-known among biology teachers. For this idea to function as a perspective in a knowledge development process, it needs to be reformulated as a question or a set of questions (Fig. 14.2). The functional perspective enables students to develop knowledge concerning biological systems by means of redesigning the system at hand. The teacher introduces this way of thinking by modeling redesign of another biological system. Students use the biological functional perspective for developing knowledge about a property (structure or behavior) of an organism (in this case: making a web), by using the questions that belong to the biological functional perspective for guidance in redesigning and evaluating the property they are investigating (see below) in several subsequent cycles (see also Janssen and Waarlo 2010 for applications of this strategy in biology education; Green et al. 2015 for applications of this strategy in biological research).

In the fragment of student discourse presented here, Kim tried to come up with the simplest possible design for a spider web, whereas Marc tried to formulate what disadvantages Kim's redesign proposal had for the organism. This can lead to adjustment of the "solution" or to the formulation of a new problem.

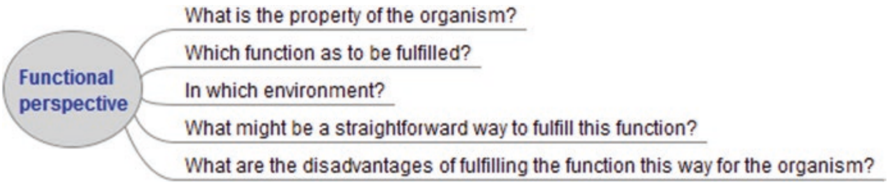


Fig. 14.2 Aspects of the biological functional perspective

Kim: Well that is simple. He [*the spider*] sticks the thread to the tree and walks down across the ground to the other tree.
Marc: Yes, but that certainly has a disadvantage. Then the thread would rip apart when he walks to the other tree.
Kim: I have a better idea. A sort of kite. He sticks the thread to the kite and the wind blows it to the other tree.
Marc: Well then the wind has to blow in the right direction by accident. But okay.
Kim: Okay, then he does it a few times so that he has a few threads and can go make the circles.
Marc: Yes but then a fly will walk away if he catches a fly. That is a disadvantage.
Kim: Than we have to make the threads sticky.
Eric: But then the spider will stick to his own web.
Marc: Eh, how do we do this. Shall we look at the whiteboard?

This fragment of student discourse shows how the functional perspective directs the knowledge development of the students about how spiders make a web. At a certain point they made use of problem 2 that the teacher had put on the whiteboard. After 10 min the students were given the assignment to compare their theories to the video that shows how a spider makes a web.

We described how students can learn to use a certain perspective for thinking about complex problems. However, to develop an understanding of the possibilities and limitations of a domain-specific perspective or way of thinking, reflection on the perspective used is necessary. Insight in the assumptions that underlie a perspective can be developed by using examples that the assumption does not apply to. In this case the teacher can, for example, ask the students what the function is of our chin, or the noise that our heart makes. The properties in these examples do not fulfil a function. Some properties are side effects of properties that do have a function. The cross on the back of the spider, for example, does not have a function in itself (Fig. 14.1). A spider secretes waste through little tubes and this becomes visible in the form of a cross. By means of this kind of examples, students become more aware of assumptions underlying a perspective and subsequently in which case it is useful to use the perspective and in which case not.

14.3.2 *Perspective-Directed Knowledge Development in Chemistry Education: Using a Particle Perspective*

Students need to understand that to explain behavior of matter, you need knowledge not only concerning particle types and types of chemical bonding (and their strengths) but also concerning organization of particles. A regular chemistry lesson to 16- to 17-year-old A-level students would typically start with an explanation of how particles of different types of matter are typically organized, given the chemical bonds between the particles (Fig. 14.3). A logical connection would be made with what they already learned: how organization and movement of particles explain the behavior of substances in different phases. This knowledge is used to explain about how chemical bonds and their strengths determine how particles of molecular substances, salts, and metals are organized at room temperature. To explain how the organization of particles, as an emerged property of particles and bonding between those particles, influences behavior, models of organized particles can be used. Next students work on part tasks such as: explain why ice floats on water or explain how water molecules are organized around sodium chloride ions when sodium chloride is solved. The lesson ends with a more complex task (this might be homework): both graphite and diamond consist of carbon atoms. However, both substances behave totally different: diamond is, for example, one of the hardest substances that we know, whereas graphite, which is used in pencils, is very "soft." You can easily

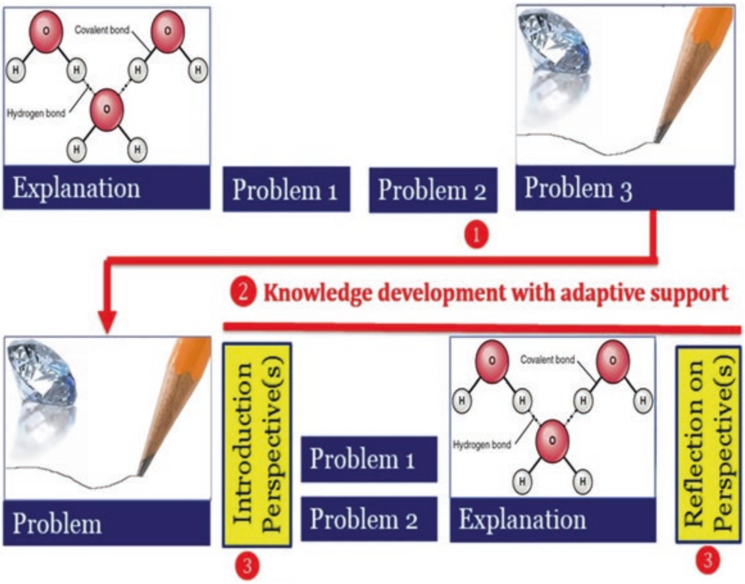


Fig. 14.3 Three heuristics for converting regular science lessons into perspective-based knowledge development. Exemplified for teaching about the organization of particles

wipe off ultrathin layers from graphite. How can you explain this difference? To solve this latter problem, all branches of the particle perspective are needed both to understand the problem (the differences) and to find an answer.

In the reversed lesson, the diamond-graphite problem is brought to the fore (Fig. 14.3). By emphasizing the strangeness of the case (why are these substances *so* different), students are stimulated to solve the problem. The particle perspective is offered as a tool for thinking about it: what type of bonding is possible between carbon atoms and what are relative strengths of these chemical bonds? And of course, how are the carbon particles possibly organized in both substances? If students need support, the teacher can offer them the part tasks about water and ice and the difference in boiling point between 2,2,-dimethylpropane and *n*-pentane.

A simple version (we call it an entry version) of the particle perspective was provided by the teacher to support knowledge development (see Fig. 14.4). Below is a fragment of the discussion that emerged in a group of three students (16 years old, A level) working on the diamond-graphite problem (T = teacher/S = student):

S1: The nature of the particles is the same: all C-atoms.

S2: The bonds should be different, so there should be another structure too.

S1: Diamond is harder, so the bonds are stronger. Graphite has weaker bonds; the material breaks off more easily.

S3: Which bonds are strong? Ionic bonds? O no, that’s stupid, both materials are molecular. There can’t be ionic or metal bonds.

S1: Can you melt diamond?

S2: Perhaps it’s like coal: one big molecule.

S3: Diamond doesn’t look like carbon.

S1: Okay, let’s focus on the bonds.

S2: Graphite could be more like in rows, like a metal, you can shove off a layer, not like with a salt.

S3: Diamond can be a lattice, a crystal lattice; that’s why, it is so strong.

S2: But does that mean a different bond or a different organization?

S1: How could there be different bonds?

S2: Single bonds or double atomic bonds?

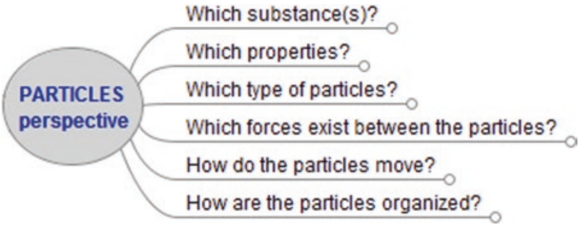
S2: So, in diamond, all atoms are linked with double bonds.

T: Could you draw that option?

S2: [Draws]

S1: No, that’s not good, you only make a very long molecule, no crystal. I don’t think triple bonds would work either.

Fig. 14.4 Particle perspective: entry version



S3: I think there should be more symmetry.
It should have something to do with differences in bond strength.
T: Why didn't you consider Van der Waals forces?
S1: I didn't think carbon atoms could form molecules.

In this example, students reasoned that the differences between diamond and graphite might be explained by the strengths of the bonds between the particles and by the organization of those particles. As the type of particles (C-atoms) and the property of the substances (hardness) were already given, certain bonds and movement were ruled out. Students used the particle perspective to explore options, focusing on the questions "what forces exist between particles?" and "how are the particles organized?" They extended these branches of the particle perspective with different options they knew exist, i.e., differences in organization of particles in diamond (crystal lattice) and graphite (rows), and the possibility of double and triple bonds between the C-atoms in diamond (see Fig. 14.5). However, they considered different covalent bonds, but did not consider the possibility of Van der Waals forces between large particles, which would imply big molecules of carbon as an option. Although differences in organization of the particles are suggested to explain the different properties between graphite and diamond, this train of thought is not pursued further in this fragment (but might have led to the idea of "big molecules").

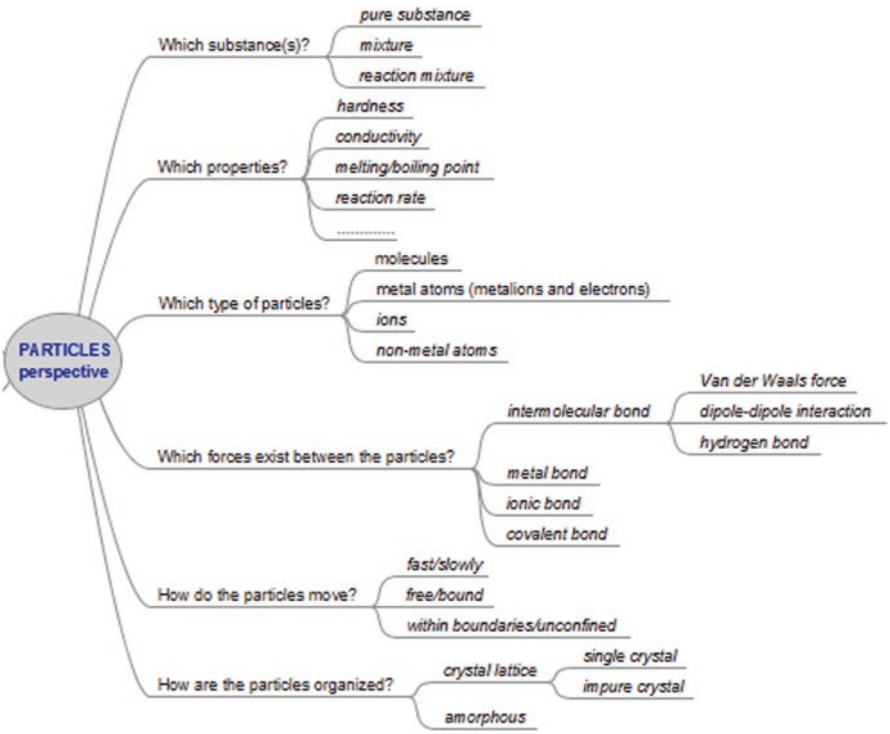


Fig. 14.5 Particle perspective: more advanced version

14.4 How Can Perspective-Based Knowledge Development Contribute to Understanding of General Aspects of Nature of Science?

The examples of the spider web and the diamond/graphite problem show how teachers can redesign their regular lessons into lessons that support perspective-directed knowledge development relatively easy. They show how perspectives can support students in developing scientific knowledge. At the same time, students become familiar with domain-specific ways of reasoning that belong to specific perspectives, the assumptions that underlie these perspectives, the questions that are connected to specific perspectives, and how answers can be constructed and tested. After participating in this type of knowledge development processes in the context of different domains, the teacher can reflect with the students on their experiences and on more general aspects of NOS (Table 14.1). In this final section we elaborate the relation between the perspective approach to knowledge development and general aspects of NOS (McComas and Kampourakis 2015).

Therefore we rephrased the NOS core aspects as questions (Table 14.1). Students can be stimulated to think about these questions drawing on their experiences with knowledge development about topics, using multiple perspectives. Reflection on general aspects of NOS can also be stimulated using historical cases, such as the case of Pauling and Burnet discussed in a previous section (Allchin et al. 2014; for an overview of historical case studies that are already available, see Allchin 2012). We will discuss how the NOS core questions can be addressed. For this we draw on widely shared ideas in the philosophy of science on the role of general searchlights for knowledge development (Kuipers 2007). More specifically, we draw on scien-

Table 14.1 Core aspects of NOS rephrased as questions

Core aspects of the nature of science associated in three domains	Questions
Human elements in science	What aspects of science are subjective?
	Is creativity vital to progress in science?
	Does science depend on social and cultural factors?
Tools and products of science	Is evidence required in science? What counts as evidence?
	Does science follow a stepwise plan?
	What is the nature of laws and theories?
Special nature of scientific knowledge	How does science differ from technology and engineering?
	Is science tentative, durable, and self-correcting?
	Does science have limits?

tific perspectivism as a recent and advanced approach on knowledge development that emphasizes the important role of perspectives for knowledge development. Important representatives of scientific perspectivism are Giere (2010a, b), Wimsatt (2007), and Callebaut (2012). For an overview, see Janssen and Van Berkel (2015).

14.4.1 Domain #1: Human Elements in Science

Subjectivity Is a Factor Scientific perspectivists assume that there is a reality that is independent from human knowledge construction (Giere 2010a; Wimsatt 2007). However, our knowledge of reality is always constrained by our perspectives and incomplete. We cannot achieve a "view from nowhere" (Wimsatt 2007). Our mind does not function as a bucket that fills itself with "true knowledge" by unprejudiced observation. Instead, our mind is more like a searchlight; our interests and perspectives determine what kind of questions we ask and what kind of knowledge we will develop. This "orientation" aspect can come to life when students reflect on their own experiences and how they use multiple perspectives as search lights. Also historical cases can be used to make insightful how multiple perspectives functioned as search lights that illuminate different aspects of the situation. Take, for example, the case of Pauling and Burnet that shows that two perspectives were needed to solve the antibody formation problem. But this does not mean that "anything goes." Scientific perspectivists argue that although perspectives are not empirically testable themselves, the knowledge developed within a perspective can and should be critically tested (Giere 2010a).

Creativity Is Vital Knowledge does not pour in our minds when we use our senses well; instead, knowledge development requires a creative leap. This applies to knowledge development within a perspective, as well as to the development of new perspectives. The development of the evolutionary perspective or the perspective of classical mechanics demanded enormous creative thinking, as it required the adjustment of, or even letting go of common assumptions and ideas (Thagard 2012).

There Are Social and Cultural Influences Because we are human, social and cultural factors do always play important roles in the choice of perspective (Thagard 2012). We can illustrate this with the case of Pauling that we discussed earlier. Pauling's research, for example, was not directed by biomedical problems at all at first. Shifts in the type of research funded at the time forced Pauling to do so (Nakamura and Csikszentmihalyi 2001). Since inter- and intramolecular forces were his expertise, he approached the new research area from this perspective.

14.4.2 Domain #2: Tools and Products of Science

Evidence Is Required Although social and cultural factors play important roles in our choice of perspective and the formulation of our expectations, we always need to critically assess our expectations by conducting experiments (Giere 2010a; Callebaut 2012). The case of Burnet and Pauling additionally shows that a perspective determines for a great part what data seem as relevant in order to test specific expectations. Pauling tested his direct template model with data on chemical bonding. Burnet collected data that followed from the biological functional perspective to test his model.

Science Shares Methods But No Shared Step-By-Step Plan Scientific knowledge development has three aspects: formulation of a question or problem, formulation of a tentative answer, critical testing of these answers (Popper 1973). As we have seen in the example of Pauling and Burnet, all three aspects are biased by the chosen perspective (Wimsatt 2007). As a result, there is no uniform protocol for conducting science that we can teach students. Instead, students need to develop different perspectives, such as the biological functional perspective and the chemical particle perspective, and learn how different perspectives might lead to different questions, possible (parts of) answers and ways to test those answers. In this way, perspectives can become thinking tools for investigating certain situations (Janssen and van Berkel 2015).

Nature of Laws and Theories Scientific perspectivism argues that knowledge has a hierarchical structure (Giere 2010b). At the top of the hierarchy are the assumptions that are fundamental to the perspective at hand. When descending in the hierarchy, knowledge becomes increasingly concrete. Figure 14.4 represents a fragment of the knowledge hierarchy within the chemical particle perspective. A knowledge hierarchy implies that knowledge development within a perspective starts with a general idea (properties of substances can be explained by properties of particles), which is then gradually elaborated in detail through the process of science (different possible properties of substances and particles). This can be seen as progressive differentiation of the perspective. When students develop knowledge using perspectives, such as the chemical particle perspective, this will result in increasing branching of the perspective (see Fig. 14.5). By comparing multiple perspective "trees," the hierarchical structure of perspectives can be made insightful. Besides differentiation, it is also possible to further generalize a perspective. The evolutionary perspective is a good example of this. Initially, three conditions for evolution by selection (variation, heredity, and differential fitness) were only applied for explaining the evolution of new functional properties of organisms and new species. This perspective was generalized by different authors. It may now be applied to explain a variety of phenomena that include a form of adaptation, e.g., in neurology, immunology (clonal selection model), human sciences, chemistry, and epistemology (Bickhardt and Campbell 2003). Students can also be stimulated to verify to what extent a particular perspective that they used in one domain (e.g., biology) can be applied in another domain (e.g., technology). The biological functional perspective that we discussed using the spider web example has many communalities but also differences with a technological structure-function perspective. By exploring the communalities and differences, students develop insight in which aspects can be generalized, and which aspects cannot. In both cases, it is, for example, assumed that a structure has multiple functions. However, from the biological perspective, those functions are always connected to survival and reproduction, whereas from a technology perspective, different types of functions are possible.

14.4.3 Domain #3: The Special Nature of Scientific Knowledge

Science Is Distinct from Technology and Engineering Technology and engineering are essentially about the question how a current situation can be transformed to a desired situation. In science, the core questions are "what is the case?" (description of the situation) and "why is this the case?" (explanation of the situation). Although the questions and methods differ, scientists make use of technology in their investigations. Technology can even deeply influence science. It produces tools that enable us to create observations that greatly extend our limited possibilities as human beings (e.g., MRI scans, telescopes, electromicroscopes). New discoveries by new technologies can lead to whole new research fields (e.g., the discovery of bacteria by van Leeuwenhoek) (Giere 2010a).

Science Is Tentative, Durable, and Self-Correcting Both absolutism and relativism are avoided within perspectivism. Scientific perspectivists and relativists agree that knowledge is not absolute, but is a human construct (Bunge 2006). However, as we remarked before, scientific perspectivists argue that though perspectives are not empirically testable themselves, development of perspective-based knowledge is and should be testable (Callebaut 2012). Therefore, knowledge can be improved so that it fits the real world better than before, but knowledge is always fallible and connected to a perspective (Wimsatt 2007; Giere 2010a). To clarify this general aspect for students, a series of historical cases that concern the same topic can be elaborated (see, for immunology, Silverstein 2009).

Science Has Limits We are only able to perceive limited aspects of reality (Giere 2010a). Scientific perspectivism acknowledges the perspectival character of our knowledge. A perspective always provides a partial and incomplete picture of the world. There are some problems that can be solved without bringing information from outside the perspective. Many problems, however, require a coordination of information from multiple perspectives (Wimsatt 2007). The need for multiple perspectives can be illustrated by many historical and topical cases. Also ethical and social aspects can come to the fore, for example, genetic testing, plastic soup, and climate change.

In this contribution we discussed an approach to teaching NOS that differs in three aspects from other dominant approaches to teaching NOS. First of all, our approach integrates a "general aspects" approach to teaching NOS and a domain-specific approach to teaching NOS. Additionally, we acknowledge in our approach the central role of perspectives in knowledge development, as epistemic and directive scaffolds for articulating questions, and assessing tentative solutions. Finally, we explicitly acknowledge that teachers have limited time, resources, and capacity in their regular practices for developing NOS teaching approaches. To meet the criterion of practicality, we developed three *practical* tools for redesigning regular lessons into lessons that support teaching NOS this way.

References

Allchin, D. (2012). The Minnesota case study collection: New historical inquiry cases for nature of science education. *Science & Education, 21*, 1263–1282.

Allchin, D. (2013). *Teaching the Nature of Science: Perspectives and Resources*. St Paul: SHiPS Education Press.

Allchin, D., Andersen, H. M., & Nielsen, K. (2014). Complementary approaches to teaching nature of science: Integrating student inquiry, contemporary cases and historical cases in classroom practice. *Science Education, 98*, 461–486.

Bickhard, M. H., & Campbell, D. T. (2003). Variations in variation and selection: The ubiquity of the variation-and-selective-retention ratchet in emergent organizational complexity. *Foundations of Science, 8*(3), 215–282.

Bunge, M. (2006). *Chasing reality: Strife over realism*. Toronto: University of Toronto Press.

Burnet, F. M. (1957). A modification of Jerne's theory of antibody production using the concept of clonal selection. *The Australian Journal of Science, 20*(3), 67–69.

Callebaut, W. (2012). Scientific perspectivism: A philosopher of science's response to the challenge of big data biology. *Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences, 43*(1), 69–80.

Duschl, R. A., & Grandy, R. (2013). Two views about explicitly teaching nature of science. *Science & Education, 22*(9), 2109–2139.

Giere, R. N. (2010a). *Scientific perspectivism*. Chicago: University of Chicago Press.

Giere, R. N. (2010b). An agent-based conception of models and scientific representation. *Synthese, 172*(2), 269–281.

Green, S., Levy, A., & Bechtel, W. (2015). Design sans adaptation. *European Journal for Philosophy of Science, 5*(1), 15–29.

Hodson, D. (2014). Nature of science in the science curriculum: Origin, development, implications and shifting emphases. In *International handbook of research in history, philosophy and science teaching* (pp. 911–970). Dordrecht: Springer.

Janssen, F. J. J. M., & van Berkel, B. (2015). Making philosophy of science education practical for science teachers. *Science & Education, 24*(3), 229–258.

Janssen, F. J. J. M., & Waarlo, A. J. (2010). Learning biology by designing. *Journal of Biological Education, 44*(2), 88–92.

Janssen, F. J. J. M., Westbroek, H. B., Doyle, W., & van Driel, J. H. (2013). How to make innovations practical. *Teachers College Record, 115*(7), 1–43.

Kampourakis, K. (2016). The "general aspects" conceptualization as a pragmatic and effective means to introducing students to nature of science. *Journal of Research in Science Teaching, 53*(5), 667–682.

Kuipers, T. A. (2007). Laws, theories and research programs. In D. M. Gabbay, P. Thagard, J. Woods, & T. A. Kuipers (Eds.), *General philosophy of science: Focal issues* (pp. 1–97). Amsterdam: Elsevier.

Lederman, N. G., & Lederman, J. S. (2014). Research on teaching and learning of nature of science. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of research on science education, Vol 2 (30)* (pp. 600–620). New York: Routledge.

McComas, W. F., & Kampourakis, K. (2015). Using the history of biology, chemistry, geology, and physics to illustrate general aspects of nature of science. *Review of Science, Mathematics and ICT Education, 9*(1), 47–76.

McComas, W. F. (2008). Seeking historical examples to illustrate key aspects of the nature of science. *Science & Education, 17*(2–3), 249–263.

Nakamura, J., & Csikszentmihalyi, M. (2001). Catalytic creativity: The case of Linus Pauling. *American Psychologist, 56*(4), 337.

Niaz, M. (2011). *From 'Science in the Making' to Understanding the Nature of Science*. An Overview for Science Educators. Routledge.

Pauling, L. (1940). A theory of the structure and process of formation of antibodies. *Journal of the American Chemical Society, 62*(10), 2643–2657.

Popper, K. (1973). *Objective knowledge*. Oxford: Clarendon.

Schwab, J. J. (1962). The teaching of science as enquiry. In J. J. Schwab & P. F. Brandwein (Eds.), *The teaching of science*. Cambridge, MA: Harvard University Press.

Silverstein, A. M. (2009). *A history of immunology*. Academic Press.

Thagard, P. (2012). *The cognitive science of science: Explanation, discovery and conceptual change*. Cambridge, MA: MIT Press.

Wimsatt, W. C. (2007). *Re-engineering philosophy for limited beings: Piecewise approximations to reality*. Cambridge: Harvard University Press.

Chapter 15
Framing and Teaching Nature of Science as Questions

Michael P. Clough

15.1 The Importance of Framing and Teaching the NOS as Questions

More than a decade ago, I put forward serious concerns about framing nature of science (NOS) issues as tenets for science teaching and learning (Clough 2007). I made clear that while general agreement may, for the most part, exist among science educators regarding particular NOS issues, rendering NOS learning outcomes as tenets ignores, or at the very least does not promote, attention to context, nuance, and complexity. My misgivings are shared by many other science educators (e.g., Allchin 2011; Eflin et al. 1999; Elby and Hammer 2001; Erduran and Dagher 2014; Hodson 2008; Matthews 2012; Rudolph 2000). The issues that I and others have raised about NOS tenets include, but go beyond, what NOS content should be taught and learned. Central to my concerns about NOS tenets are the purposes of education and how tenets do not promote meaningful NOS understanding. For instance:

> …tenets, like established scientific knowledge, become something to be taught rather than investigated in a science classroom. For students the tenets become something to know rather than understand. (Clough 2007, p. 1)

Let me be clear that this is not the intent of those who put forward and support NOS tenet statements. But as Duschl (1990) noted in referring to the presentation of science content knowledge in its final form, “When the structure and role of theories are oversimplified, there is little need to accurately portray the processes of theory change” (p. 69). Similarly, the simplified structure of NOS tenets conveys little need to accurately address accompanying arguments, counterarguments, context, and

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_15

nuances to promote a NOS understanding that can be thoughtfully applied in a variety of contexts. Advocates of NOS tenets optimistically maintain that teachers will accurately translate them, but tenets are easily seen as learning outcomes that establish a low ceiling for teaching and learning.

Framing NOS issues as questions deliberately avoids two extreme positions that have fundamental weaknesses. Tenets reflect a mode of thought that McKeon (2016) labels *construction* and Owen (2003) calls *atomism*. This mode of thought is pervasive in schooling and is reflected in detailed learning outcomes and aligned assessments. This perspective has tragically often resulted in the narrowing of schooling to value only those things that can be clearly described as "outcomes" and measured. At the other extreme, some maintain that the NOS is too complex and varied to establish a position on precisely what students should learn, a mode of thought called *discrimination* (McKeon 2016) or *perspectival* (Owen 2003). My view is that the discrimination/perspectival mode of thought is not practical for much of schooling, and the construction/atomism position is antithetical to *education*. My position regarding framing and teaching the NOS via questions reflects McKeon's *resolution* mode of thought whereby problems and the inquiry into those problems are at the forefront of NOS teaching and learning. This entails extensive use of arguments, attention to context and important nuances, and the development of reasoned positions regarding important NOS questions. Framing the NOS as questions calls for and encourages both teachers and students to more deeply think about NOS issues, and promote thinking, the understanding of arguments, and the contextual nature of claims regarding the NOS.[1]

15.2 NOS Questions to Explore in Science Education

The kinds of NOS questions that I maintain ought to guide science education efforts appear in Table 15.1. While not an exhaustive list, the questions encompass the NOS elements that frame this book, but go well beyond them and ideas appearing in other popular NOS tenets lists. They do so in two ways.

First, the questions are phrased in a way that simple responses are unsatisfactory. For instance, rather than a tenet that merely states scientific knowledge is tentative (but also durable as later tenets have noted) or that scientific knowledge has an inventive character, the questions associated with those NOS issues encourage deeper thinking, the use of multiple examples, and reasoned arguments in support of positions (i.e., the reflective thinking that research makes clear is crucial in effective NOS teaching and learning). For example, while the reality of atoms was not firmly established until early in the twentieth century, today that idea is more than durable and now reflects the way we think nature really is. So, a viable argument can

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[1] I am indebted to Dr. Joanne Olson for insights into McKeon's work regarding modes of thought. See McKeon, R. (2016). *On knowing: The social sciences*. D. B. Owen & J. K. Olson (Eds.). University of Chicago Press, Chicago, IL.

Table 15.1 Example NOS questions for science education

How are basic science, applied science, engineering, and technology similar and different? How do they impact one another and how does this illustrate that all are needed?
How does the notion of a universal step-by-step scientific method distort how scientists actually work? In what ways are particular aspects of scientists' work guided by existing knowledge and protocols?
Why is well-established science knowledge often so durable and enduring? Regardless of how durable well-established science ideas may be, why is all science knowledge still potentially open to revision or even rejection by the scientific community? How is the possibility of revisiting and revising previously established ideas a strength of science?
In what sense is scientific knowledge invented? In what sense is it discovered?
To what extent is scientific knowledge based on and/or derived from observations of the natural world? In what ways is it based on reasons other than observational and experimental evidence?
How are observations and inferences different? In what sense is an observation an inference?
How has science at times been advanced and hindered by religion? What range of perspectives regarding religion and faith do scientists bring to their work? How does complex interaction rather than persistent warfare better account for the relationship between science and religion?
How is the private work of scientists similar to and different from what is conveyed when they publicly share their work with the wider scientific community? What accounts for these differences, and how does public science mitigate personal bias and other subjective factors?
To what extent are scientists and scientific knowledge objective and subjective? To what extent can subjectivity be reduced or eliminated?
To what extent is scientific knowledge socially and culturally embedded? In what sense does scientific knowledge transcend particular cultures?
In what ways are scientific laws and theories different types of knowledge? How are they related to one another? How does each guide research directions, methods, and the analysis of data?
What purposes do scientific models serve in science? What are the strengths and limitations of scientific models?
To what extent is scientific research and knowledge the product of human imagination and creativity? What factors moderate imagination and creativity in the development and justification of science ideas?

be made that scientists have discovered something about the natural world that was not previously apparent. That does not mean the idea of atoms can never be overturned, and this important issue is reflected in the question appearing in Table 15.1 regarding the potential for revisiting and revising of established science ideas being a strength of science. Of course, NOS tenets are more straightforward than questions, but that is precisely why the content of those statements is problematic. For example, the claim that scientific knowledge is tentative is well-intentioned but also easily misunderstood and open to misuse. An editorial in the March 9, 2017, issue of *Nature*, lamenting anti-science bills that have been introduced in several states, laid some of the fault for the distrust of science at the way NOS is being presented in schools:

> Perhaps a more pressing criticism of the way NOS is taught in schools is that it encourages rather too much doubt over scientific ideas. Many findings, after all, are well established… . Not all science is tentative… (Editorial, p. 149)

Second, the questions in Table 15.1 raise several NOS issues that have surprisingly not been included in commonly advocated NOS lists for science teaching and learning. For example, addressing the differences, similarities, and interdependence between basic science, applied science, engineering, and technology is important for informed decision-making regarding governmental support for each area, and this issue takes on even greater importance given STEM education efforts that can easily exacerbate misunderstanding of these areas (Clough and Olson 2016). Another essential NOS question addresses the complex interaction between science and religion, the common misconceptions that science and religion are in constant conflict and that religion always interferes with science (e.g., Ferngren 2002; Lindberg and Numbers 1986; Olson 2004; Stanley 2007, 2015), and the perspectives that scientists bring to their work regarding religion and faith (Ecklund 2010). Given the way these issues impact the teaching and learning of science, they deserve attention in NOS instructional efforts. Another important NOS issue absent from popular NOS lists is how and why private science differs from public science. The many erroneous and sanitized views of science held by the public and the impact they can have on socio-scientific decision-making (e.g., the backlash to "climate-gate") can be traced to a lack of sufficient attention to this question.

Framing the teaching and learning of NOS issues as questions like those appearing in Table 15.1 will greatly assist in avoiding simplistic and problematic generalized NOS statements, but will require that science teachers understand NOS content and pedagogy at a level where they can effectively teach the NOS through an inquiry approach—having at their disposal general NOS statements simply won't suffice! While advocates of NOS tenets may maintain that teachers must unpack the tenets in the way I have put forward, tenets do not promote that effort and, like most learning outcome standards, appear as a checklist of ideas students must know. Despite the well-intentioned nature of NOS tenets, like all statements of final form knowledge in universal schooling, they inadvertently set and support a low ceiling for teaching and learning.

15.3 Exploring NOS Questions with Students

McKeon's (2016) resolution mode of thought structures content as problems to be explored. The following two examples illustrate the framing and teaching of NOS as questions, and how questions can draw students' attention to important NOS issues and assist them in developing more informed NOS understanding. Both are more extensive and detailed accounts of what appeared in Clough (1997) where I wrote about how I explicitly and consistently incorporated the NOS when teaching high school science. The first example demonstrates how I engaged students in comparing private science to public science, and the second example shows how I had students explore the similarities, differences, and interdependence of basic science, applied science, engineering, and technology. Both examples illustrate how framing the NOS as questions to be explored guided my NOS pedagogy and the way students learned about the NOS.

How is the private work of scientists similar to and different from what is conveyed in sharing their work with the wider scientific community? What accounts for these differences, and how does public science mitigate personal bias and other subjective factors?

Effectively teaching science through inquiry not only mentally engages students in learning science content at a deeper level, but it also creates many opportunities for addressing the NOS. In the classroom example presented here, my students worked in small research teams to determine the products of a chemical reaction. Plausible tests, what lab equipment to use, whether a mathematical approach would be helpful, and what data would be meaningful or not for determining the reaction products were just a few of the questions that students had to consider in their efforts. While some research teams' initial work reflected elements of trial-and-error thinking, that approach soon gave way to using the chemistry knowledge previously learned in class to make reasoned speculations about possible products. For instance, using their understanding of the well-established idea that atoms are not created or destroyed in chemical reactions, students limited the possible products to those that contained elements appearing in the reactants. Prior nomenclature and chemical bonding knowledge was also used in putting forth possible products. Groups attempted to create balanced equations with their speculated products, drawing from their chemistry knowledge that if an equation cannot be balanced, then such a reaction could not occur.

Students soon began making extensive use of the Merck Index, a compendium of information about chemicals, to determine what physical and chemical properties were associated with their speculated products. Much investigation ensued as students wrestled with how to separate the products and test their chemical and physical properties. Some students had the insight that applying stoichiometry could provide quantitative evidence for or against particular products. Data collected required analysis, and issues of ambiguity often arose. Small research teams began working with other research teams, sharing ideas, data, and interpretations. Data at times was deemed not credible. Procedures were reassessed, multiple trials were conducted, and students' satisfaction with results increased when coherence was achieved. But disagreements occurred within and among groups, and these were often, but not always, settled to everyone's satisfaction. Over the several days that their inquiry took place, many approaches were begun, modified, and abandoned. Other approaches were deemed fruitful and maintained. Much debate occurred regarding viable paths to answer the research question, what data was meaningful or trustworthy, how confidence could be achieved, and so on. General agreement often resulted, and some years students became very confident in their conclusions.

Prior to this activity, I assigned students to keep a journal regarding their efforts and include everything related to their work—where they were when their ideas emerged, issues that arose when working with others in and outside their research team, who raised ideas, how ideas were received by others, what ideas were immediately rejected and why, ideas that were abandoned through the process and why, ideas that were abandoned and later resurrected, personality conflicts, etc. In addition to ensuring students were making such entries in their journal, my role during the activity was to pose questions that maintained student engagement in the laboratory investigation and redirect their questions to their laboratory procedures, evidence acquired, and interpretations made. I never told students what data to collect, what tests to run, how to interpret their data, or what conclusions were valid or invalid. Rather, I asked questions that directed their attention to the decisions they had made or were struggling to make to bring to the forefront their thinking. Students experienced a great deal of the frustration, enjoyment, success, and uncertainty inherent in doing science.

At the end of this extensive inquiry experience, I told students to presume I was the editor for a research journal, and each research team was to submit to my journal a paper regarding their work. I provided students the requirements for publication that are found in typical research journals. After their research papers were turned in, I reminded students to complete their personal journal entries regarding their work and bring those to the class the following day. That night I reviewed their research journal submissions and made comments regarding the clarity of their writing and reasoning for their conclusions. The following day I began by having students individually review their personal journals for approximately 5 min and then get together with their research team and share with each other entries of their choosing. After 10 min of sharing, I then returned their submitted research journal papers with my comments and asked questions like the following:

- How is the description of your work appearing in your personal journals different from what appeared in your submitted scientific paper?
- How is the work described in your personal journals similar to what appeared in your submitted scientific paper?
- What accounts for these differences and similarities? What do other scientists need to know and want to know about your research work? What is likely not important to them? Given all this, what are the purposes of scientific papers?
- How does your submitted scientific paper compare with the “scientific method” that is commonly taught in science classes? How does this compare to your actual work?
- What subjective factors appear in your personal journal entries that do not appear in your scientific papers?
- Given the many subjective factors that you note appear in your personal journals, how were these subjective factors reduced? How was confidence in your work eventually achieved?
- In what sense do the work, data, and conclusion appearing in your submitted scientific paper come across as objective knowledge? In what sense is your final thinking far less subjective, yet not totally objective?

I ask many more questions to draw students’ attention to other NOS issues in Table 15.1 that are linked to private and public science. Knowing that students may be skeptical regarding how their work compares to the actual work of scientists (Clough 2006), I then had students read “Is The Scientific Paper a Fraud?” (Medawar 1963). Medawar, a co-recipient of the 1960 Nobel Prize in Physiology/Medicine, argued that scientific papers sanitize (by omission rather than deliberate design) how science research actually works, making it appear to be a fairly straightforward inductive and objective process. How private science compares to public science can be further emphasized by showing portions of the *Mechanical Universe and Beyond* program that presents Robert Millikan’s oil drop experimental work, data, and efforts to make sense of those data (https://archive.org/details/The_Mechanical_Universe_and_Beyond_12_The_Millikan_Experiment). This and many other examples (e.g., Watson’s (1969) *The Double Helix*) are useful for convincing students how private science differs from public science, but how subjective factors in private science are mitigated as research is shared with and evaluated by the wider scientific community. Finally, asking the following kinds of questions is important to help students think about how science journal articles serve a different purpose than conveying all that goes into private work of scientists.

- What information do scientists want to see in research published in journals? Why is that information crucial?
- What information do scientists unlikely want to see in published journal articles? Why is that the case?
- What purpose do science research publications serve and what purpose do they not serve?

Framing and teaching the NOS in this manner promotes a deeper understanding of scientists’ work that would assist in more accurately interpreting socio-scientific issues such as the unfortunate climategate public controversy (Allchin 2011).

How are basic science, applied science, engineering, and technology similar and different? How do they impact one another and how does this illustrate that all are needed?

Careful and overt attention to the characteristics of basic science, applied science, engineering, technology, and their interactions is necessary for understanding how each is important and deserving of funding. To engage students in the questions above, I first provided them a brief description and rationale for nine research projects that I selected. Unbeknownst to students, three of the nine were basic science research projects, three were applied science research projects, and three were engineering research projects. The nine projects appeared in no particular order. I instructed students to carefully consider each research project and prioritize them from most deserving to least deserving of public funding. I then asked them to decide what percent of the total available funds should be directed to each project. Unsurprisingly, most students prioritized the three engineering research efforts to create technologies, followed by the applied science research projects, and the basic science projects last. When asked to explain their preferences for funding, students overwhelmingly argue that the projects they rank most worthy of funding will likely improve human life while the research efforts ranked at the bottom have no practical utility. Students' allotment of funds followed this same trend, and many students refused to provide any funding to what they would later learn is called basic or fundamental research. Students' thinking conveys that they value engineering and applied science, but not basic science.

I then had students read a newspaper article (Bednarek 1993) showing how a particular research project they had strongly supported was dependent upon the research projects that they claimed were a waste of money. After students completed this reading, I asked questions such as:

- Had the research projects you claimed were a waste of public money not been supported in the past, how would that have impacted the research projects you now wish to fund?
- If we were to place the nine research projects into three groups, which projects would be grouped together? Comparing your three groupings, what is different in what they seek to accomplish? What is similar in what they seek to accomplish?

When I have taught this lesson more recently, at this point I show a portion of an interview with astrophysicist Neil deGrasse Tyson (2011) where he addresses what science seeks to accomplish and how basic science research impacts technological development in ways that cannot be anticipated. In the interview, he states:

> This notion that science is the path to solve your problems; I think that misrepresents what drives scientists. Do you think when you speak with Brian Green he's going to say, "I am trying to come up with a coherent understanding of the nature of reality so that I can solve people's problems?" Do you think that's what driving him? Do you think I'm being driven when I look at the early universe or study the rotation of galaxies or the consumption of matter by black holes, do you think I'm being driven by the lessening of the suffering of people on Earth? Most research on the frontier of science is not driven by that goal—period! Now, that being said, most of the greatest applications of science that *do* improve the human condition *come* from just that kind of research. Therein is the intellectual link that needs to be established in an elective democracy where tax-based monies pay for the research on the frontier. …The purpose of science is to understand the natural world. And the natural world has, interestingly enough, built within it forces and phenomena and materials that a whole other round of clever people—engineers, in the case of the magnetic resonance imager—these are biomedical engineers basing their patents and their machine principles on physics discovered by a physicist, an astrophysicist at that. So I take issue with the assumption that science is simply to make life better. Science is to understand the world. Now you have a utility belt of understanding. Now you access your tools out of that, and use those, that ever increasing assortment of power over nature, to use that power in the greater good of our species. You need it all.

I then provide three historical examples (i.e., Manhattan project, Race to the Moon, and the War on Cancer) illustrating the role that knowledge gained from basic science plays in engineering efforts and vice versa. I emphasize that building an atomic bomb and landing a human on the Moon were both accomplished within a decade because the fundamental knowledge of nature necessary for accomplishing those two ends was already in hand. In contrast, when United States President Richard Nixon in 1971 declared a war on cancer, such knowledge was not available, and the effort to cure cancer, while making progress, continues today. I then return to the three groupings put forward by students and label them "Basic Science," "Applied Science," and "Engineering." The table appearing in Fig. 15.1 is presented to students, and they are instructed to think about each empty box as they read articles like the following.

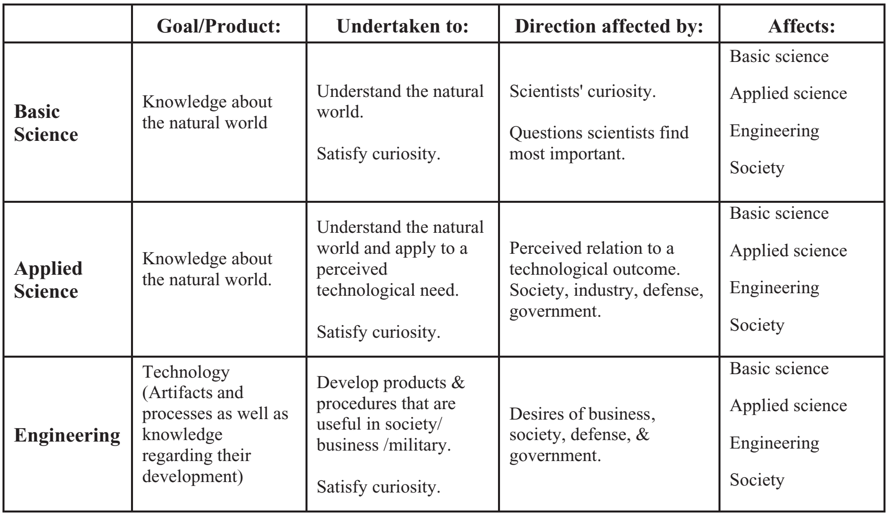
- Feynman, R.P. (1955). The Value of Science. In Feynman, R.P. (1988) *What Do You Care What Other People Think?* New York: Norton.
- Medawar, P.B. (1973a). The Cost-Benefit Analysis of Pure Research. In Medawar, P.B. (1990) *The Threat and the Glory: Reflections on Science and Scientists*. New York: HarperCollins.
- Medawar, P.B. (1973b). The Pure Science. In Medawar, P.B. (1990) *The Threat and the Glory: Reflections on Science and Scientists*. New York: HarperCollins.
- National Institute of Health (2017). Curiosity creates cures: The value and impact of basic research. https://www.nigms.nih.gov/Education/Documents/curiosity.pdf
- National Institute of Health (2011). Why do basic research? https://publications.nigms.nih.gov/basicresearch/

Together as a class, we begin the process of filling in each blank box appearing in Fig. 15.1. Students will at times suggest simplistic answers, so additional questions that play off students' suggestions are required throughout the process to tease out important nuances. Through this process, something like what appears in Fig. 15.2 results.

What appears above reflects an initial effort exploring with students the questions regarding how basic science, applied science, and engineering are similar, different, and mutually dependent upon one another. These questions are revisited in a variety of contexts during the school year along with issues regarding the nature of technology (Clough et al. 2013). Again, framing and teaching the NOS as questions encourages a richer understanding of issues that is important in personal and societal decision-making.

	Goal/Product:	**Undertaken to:**	**Direction affected by:**	**Affects:**
Basic Science				
Applied Science				
Engineering				

Fig. 15.1 Characteristics of basic science, applied science, and engineering



	Goal/Product:	Undertaken to:	Direction affected by:	Affects:
Basic Science	Knowledge about the natural world	Understand the natural world. Satisfy curiosity.	Scientists' curiosity. Questions scientists find most important.	Basic science Applied science Engineering Society
Applied Science	Knowledge about the natural world.	Understand the natural world and apply to a perceived technological need. Satisfy curiosity.	Perceived relation to a technological outcome. Society, industry, defense, government.	Basic science Applied science Engineering Society
Engineering	Technology (Artifacts and processes as well as knowledge regarding their development)	Develop products & procedures that are useful in society/ business /military. Satisfy curiosity.	Desires of business, society, defense, & government.	Basic science Applied science Engineering Society

Fig. 15.2 Characteristics of basic science, applied science, and engineering

15.4 Standards as Cues for Teaching and Learning

The NOS questions appearing in Table 15.1 strike an important balance in NOS instruction efforts. Because NOS tenets put forth comprehensive claims that ignore context, nuance, and complexity, they are problematic at best. And NOS tenets may easily be interpreted by teachers, few who have sufficient NOS understanding, as expected learning outcomes. Thus, in seeking to correct common NOS misconceptions, NOS tenets run the risk of creating different and perhaps more dangerous misconceptions regarding science and scientists. Earlier in this chapter I noted the mistaken view that easily follows from teaching that science is tentative and how this can fuel disregard for well-established science ideas important in socio-scientific decision-making. The same can be said regarding the NOS tenet emphasizing subjectivity. Other common NOS tenets appearing in the science education literature compromise an accurate and robust understanding of NOS that can and should promote more informed personal and societal decision-making.

Of course, vague and wildly open-ended NOS questions would also be problematic. Research has made abundantly clear that science teachers and their students possess inaccurate and incomplete NOS understanding. Proponents of NOS tenets rightfully argue that teachers and students need guidance regarding the NOS. The NOS questions appearing in Table 15.1 are designed to be educative! They assist teachers and students by (1) delineating important NOS issues and ideas; (2) drawing attention to more informed ways of thinking about the NOS; and (3) raising exceptions and nuances. For instance, while the second question in the table overtly casts doubt on a universal step-by-step scientific method, it is immediately followed by a question that addresses how scientists *are* guided in their work. On inspection, the questions appearing after each bullet point in Table 15.1 purposely raise an important NOS idea/issue, provide guidance in thinking about that idea/issue, and cue attention to thinking, arguments, and reasoned responses.

Thus, framing the teaching and learning of NOS as questions is not merely a personal preference regarding semantics. Standards are a kind of technology in that they are a manufactured artifact designed to accomplish a particular end. Like all technologies, inherent in their design are cues on how they should be used. Kruse (2013) notes that

> the claw end of a hammer can be used as a flat-bladed screwdriver, but the very design of a hammer sends clear messages that it *should* be used to strike something. …although textbooks can be used as a valuable tool in classrooms, the bolded words cue students (and teachers) to place emphasis on vocabulary acquisition over deep conceptual understanding.

In the same way, the simplified nature and structure of NOS tenets cue teachers and students to particular declarative claims rather than reasoned positions and deep understanding that take into account context and complexity. Like with much schooling, a *training* often ensues rather than an *education* (Eisner 2002), and more harmful NOS misconceptions may result. Framing NOS instruction in terms of questions like those appearing in Table 15.1 sends different cues that would assist in efforts to promote NOS understanding that can be flexibly used to make more informed personal and socio-scientific decisions.

References

Allchin, D. (2011). Evaluating knowledge of the nature of (whole) science. *Science Education, 95*(3), 518–542.

Bednarek, D. I. (1993). Friction: Heat-loving bacterium roils two worlds. Business, academia spar when product of basic research proves practical. *The Milwaukee Journal*, May 9.

Clough, M. P. (1997). Strategies and activities for initiating and maintaining pressure on students' Naïve views concerning the nature of science. *Interchange, 28*(2–3), 191–204.

Clough, M. P. (2006). Learners' responses to the demands of conceptual change: Considerations for effective nature of science instruction. *Science & Education, 15*(5), 463–494.

Clough, M. P. (2007). Teaching the nature of science to secondary and post-secondary students: Questions rather than tenets. *The Pantaneto Forum*, Issue 25, (http://pantaneto.co.uk/issue-25/). Reprinted (2008) in the *California Journal of Science Education*, *8*(2), 31–40.

Clough, M. P., & Olson, J. K. (2016). Connecting science and engineering practices: A cautionary perspective. Chapter 15. In L. A. Annetta & J. Minogue (Eds.), *Connecting science and engineering education practices in meaningful ways – Building bridges* (Contemporary trends and issues in science education series). Dordrecht: Springer.

Clough, M. P., Olson, J. K., & Niederhauser, D. S. (Eds.). (2013). *The nature of technology: Implications for learning and teaching*. Rotterdam: Sense Publishers. ISBN: 978-94-6209-267-9.

DeGrasse Tyson, N. (2011). The moon, the tides and why Neil DeGrasse Tyson is Colbert's god: A conversation about communicating science. *The Science Network*, January 20. http://thesciencenetwork.org/programs/the-science-studio/neil-degrasse-tyson-2. Retrieved 1 Nov 2017.

Duschl, R. A. (1990). *Restructuring science education: The importance of theories and their development*. New York: Teachers College Press.

Ecklund, E. H. (2010). *Science vs. religion: What scientists really think*. Oxford: Oxford University Press.

Editorial. (2017, March 9). School daze: As US states turn the screw on science education, researchers everywhere should pay more attention to how their subject is presented. *Nature, 543*, 149.

Eflin, J. T., Glennan, S., & Reisch, G. (1999). The nature of science: A perspective from the philosophy of science. *Journal of Research in Science Teaching, 36*(1), 107–117.

Eisner, E. W. (2002). *The educational imagination: On the design and evaluation of school programs* (3rd ed.). Upper Saddle River: Pearson Education.

Elby, A., & Hammer, D. (2001). On the substance of a sophisticated epistemology. *Science Education, 85*(5), 554–567.

Erduran, S., & Dagher, Z. R. (2014). *Reconceptualizing the nature of science for science education: Scientific knowledge, practices and other family categories*. Dordrecht: Springer.

Ferngren, G. B. (2002). *Science & religion: A historical introduction*. Baltimore: John Hopkins University Press.

Hodson, D. (2008). *Towards scientific literacy: A teachers' guide to the history, philosophy and sociology of science*. Rotterdam: Sense Publishers.

Kruse, J. W. (2013). Implications of the nature of technology for teaching and teacher education. Chapter 17. In M. P. Clough, J. K. Olson, & D. S. Niederhauser (Eds.), *The nature of technology: Implications for learning and teaching*. Rotterdam: Sense Publishers.

Lindberg, D. C., & Numbers, R. L. (1986). *God and nature: Historical essays on the encounter between Christianity and science*. Berkeley: University of California Press.

Matthews, M. (2012). Changing the focus: From nature of science (NOS) to features of science (FOS). Chapter 1. In M. S. Khine (Ed.), *Advances in nature of science research: Concepts and methodologies*. Dordrecht: Springer.

McKeon, R. (2016). In D. B. Owen & J. K. Olson (Eds.), *On knowing: The social sciences*. Chicago: University of Chicago Press.

Medawar, P. B. (1963). Is the scientific paper a fraud? In P. B. Medawar (Ed.),. (1990) *The threat and the glory: Reflections on science and scientists*. New York: HarperCollins.

Olson, R. G. (2004). *Science & religion 1450–1900: From Copernicus to Darwin*. Baltimore: John Hopkins University Press.

Owen, D. B. (2003). *The foundations course: Depth versus breadth?* Paper presented at the annual meeting of the Midwest Philosophy of Education Sciences. St. Louis, MO. November.

Rudolph, J. L. (2000). Reconsidering the "nature of science" as a curriculum component. *Journal of Curriculum Studies, 32*(3), 403–419.

Stanley, M. (2007). *Practical mystic: Religion, science and A. S. Eddington*. Chicago: University of Chicago Press.

Stanley, M. (2015). *Huxley's church & Maxwell's demon: From theistic science to naturalistic science*. Chicago: University of Chicago Press.

Watson, J. D. (1969). *The double helix*. New York: Signet, New American Library.

Chapter 16
Using Real and Imaginary Cases to Communicate Aspects of Nature of Science

David Boersema

16.1 Introduction

This chapter features a discussion of a three-pronged course-based approach to the nature of science. Although the entire course will not be shared here, the organizational aspects of science as *doctrine*, *process*, and *social institution* have proved useful and will frame the ongoing conversation in this chapter. The notion of science as doctrine focuses on the content of the sciences, on *what* scientists investigate as their domain (as opposed to, say, the domain of arts or humanities). Many students quickly accept this notion. After all, students know that what they study in biology is quite different than what they study in foreign language courses. Science as process characterizes the sciences not in terms of *what* they investigate—even poets and philosophers talk about evolution, for instance—but in terms of *how* they study what they study. Finally, science as a social institution is an examination of the sciences as enterprises conducted by scientists as real-live members of society who reflect and shape social perspectives and values. Students are often quick to identity (and misidentify) where the sciences and society directly interface. One point to note here is that students often conflate science and technology, so when they speak to the issue of where science and society directly interface, more often than not they point to technological matters (e.g., nuclear power or communication technology) as examples.

The three prongs discussed here largely correspond with aspects of the overall nature of science in terms of the limits of scientific knowledge and process, the tools and products of science, and various human elements of science. In this chapter, I will explain how it is useful to teach aspects of the nature of science in terms of the *doctrine*, *process*, and *social institution* of science and then discuss two case studies

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_16

(one imaginary and one real) that I have found fruitful for illustrating the usefulness of this approach. This approach has proven useful because it allows students to focus on particulars that are easy to grasp and manage while at the same time showing how they serve as instances of and reflections of broader conceptual and theoretical concerns. Now, let us take each of the strands individually to see how this organizational scheme operates.

16.1.1 Science as Doctrine

With respect to science as *doctrine*, the focus is not on specific scientific claims, but on conceptual issues related to scientific claims, or "epistemic concepts" as such claims are known by philosophers of science. Such concepts are connected to science as a body of knowledge. Included in this discussion are concepts and issues such as the nature, role, and complexities of *observation*, *measurement*, *experimentation*, *laws*, *models*, and *theories*. For example, when looking at the issue of observation, it is useful to review factors that influence what is observed (or even observable), how it is observed, and why it is observed. With respect to what is observed, multiple factors arise; what is observed could include the number of organisms in a particular area or the various phenotypic traits of particular organisms. But, what is observed might also be, say, patterns or events, such as the rate of decay of some element. A matter of importance could even be what is *not* observed in a given situation, that is, the absence of some expected feature of the world. As for how *observation* occurs, one can consider the cognitive capabilities and constraints inherent in *observation*. For instance, there are numerous factors that shape human observation, such as the limitations of our sensory abilities (as an example, we can see only certain parts of the light spectrum, which is why we use instruments such as microscopes and telescopes and recording devices). There are other factors such as previous experience and training (physicians "see" tumors in an X-ray that look like blurs to the rest of us), but the doctors' preconceived notions gained through training—sometimes called "theory-based observations"—permit them to visualize things that the rest of us cannot interpret properly. Finally, with respect to why observation occurs (i.e., motivations or purposes that might be related to observations), this has to do with the fact that no scientific observation is disinterested. In science especially, we are not simply "looking at" the world, but very often "looking for" some hypothesized or expected feature. This especially can be the case depending upon who is funding the research and why, but is true of any scientific *experiment*; certain observable phenomena are being considered and others are not. In teaching the nature of science, then, helping students see that something as basic as "merely observing" things is actually quite multifaceted. The same multifaceted considerations apply to other epistemic elements of science, such as *measurement*, *models*, *theories*, etc. (Tables 16.1, and 16.2).

Table 16.1 Readings related to philosophical issues on science as doctrine (and observation) that might be useful in supporting instruction in this regard

Hanson, N. R. (1972). "Observation," in *Patterns of Discovery*. Cambridge: Cambridge University Press. Pages 4–30. This classic article argues for understanding observation not as sensory perception, but as experience, with interpretation as a necessary and ineliminable component of observation.
Jones, R. (1982). *Physics as Metaphor*. New York: New American Library. A discussion by a physicist on the conceptual complexities of basic scientific components such as observation, measurement, explanation, relation of data to theories, etc. Very readable and accessible to students.
Morrison, M. and Morgan, M.S. (eds.) (1999). *Models as Mediators.* Cambridge: Cambridge University Press. An anthology of essays on the nature of scientific models, both in the natural and social sciences, including discussions of their relation to other aspects of science, such as observation, explanation, and theories.
Radder, H. (2006). *The World Observed/The World Conceived*. Pittsburgh: University of Pittsburgh Press. A detailed examination of the complexities of observation and the cognitive, conceptual aspects of perception.
Ravetz, R. (1971). "Scientific Inquiry: Problem-solving on Artificial Objects," in *Scientific Knowledge and Its Social Problems*. Oxford: Oxford University Press. Pages 109–145. A readable examination of the fundamental nature of science as addressing conceptualized features of the world (things and events as "artificial objects"), with inherent theory-driven and value-driven aspects.
Scheffler, I. (1982). "Observation and Objectivity" from *Science and Subjectivity, 2nd edition*. Indianapolis: Hackett. Pages 21–44. This article is largely a response to, and divergence from, Hanson's claim that observation cannot be objective.

Table 16.2 Readings to support discussions of scientific change and progress

Bowler, P. and Morus, I.R. (2005). *Making Modern Science: A Historical Survey*. Chicago: University of Chicago Press. A detailed discussion of social and cultural contexts for the development of modern western science, including social, religious, and political influences.
Chalmers, A. F. (2013). *What Is This Thing Called Science?, 4th edition.* St. Lucia: University of Queensland Press. A readable introduction to different positions on the nature of scientific change and progress, including inductivism, falsificationism, historicism, and others.
Hacking, I. (ed.) (1981). *Scientific Revolutions.* Oxford: Oxford University Press. An anthology of classic articles on the nature of scientific change and progress, including readings by Thomas Kuhn, Karl Popper, Imre Lakatos, and others. A very good resource for primary source readings.
Trout, J.D. (2016). *Wondrous Truths: The Improbably Triumph of Modern Science*. Oxford: Oxford University Press. An examination of the history of modern science, with an emphasis on the philosophical and social influences and aspects of them.

16.1.2 Science as Process

With respect to science as *process*, I have found it useful to focus on various perspectives on the nature of scientific *change* and *progress*. A useful approach to doing this is to focus on historical cases as a means of highlighting how in fact Western science has changed and progressed. Again, this can be in terms of science as *doctrine* (i.e., the content of science has changed over time), science as *process* (the methods used and embraced by scientists have changed over time), and science as *social institution* (the social, political, religious, and philosophical assumptions and commitments that have influenced, and been influenced by, science have changed over time).

One approach to illustrating the nature of *change* and *progress* that I have found successful has been to focus on the historical case study of the development of *plate tectonics*. (Table 16.3 gives some useful historical summaries of this case.) Very briefly, plate tectonics is the idea that the earth's crust is constituted, in large part, by a collection of plates. These vast plates slowly move horizontally, carrying the continents (or large portions of them). While the notion of continental drift was postulated and argued for, especially by Alfred Wegener, early in the twentieth century, this view is not the same thing as plate tectonics. Wegener's views were largely rejected by contemporary geologists for a number of reasons, a major one being that no physical force was known that would allow continents to plow across the ocean floor. A fuller view of plate tectonics emerged in the middle of the twentieth century, as geologists came to understand that the continents do not move across the ocean floor, but are moved by the shifting of underlying continental plates which anchor the continents. This broader theory both corrected and encompassed the previous continental drift theory. This case provides an accessible study for students to consider whether the change in geological understanding was a matter of merely collecting more data (and inductively making inferences upon that additional data) or was, say, a matter of a sudden paradigm shift in approaching data. It provides a nice case for asking what sorts of evidence count as being falsifying or confirming (since what was seen as having falsified continental drift was later rejected as having done so). It also allows for looking at what sorts of claims were taken by geologists as appropriate for testing versus those seen as established and outside the purview of further testing (and why).

Table 16.3 References related to plate tectonics that instructors might find useful in illustrating this aspect of the geosciences

Frisch, W. and Meschede, M. (2010) *Plate Tectonics: Continental Drift and Mountain Building*. New York: Springer. A recent treatment of how contemporary geologists understand the world, given the assumption of plate tectonics.
Gohau, G. (1990). *A History of Geology*. New Brunswick: Rutgers University Press. Pages 187–200. A broad survey of the history of geology, with an accessible chapter that focuses on plate tectonics (and gives the broad historical context for its emergence).
Hallam, A. (1973). *A Revolution in the Earth Sciences*. Oxford: Clarendon Press. A detailed discussion of the emergence of plate tectonics from one of its important early proponents.
LeGrand, H.E. (1988). *Drifting Continents and Shifting Theories.* Cambridge: Cambridge University Press. A detailed discussion of the various aspects of plate tectonics, with an emphasis on how they reveal the nature of scientific inquiry and change.
Molnar, P. (2015). *Plate Tectonics: A Very Short Introduction*. Oxford: Oxford University Press. A readable overview of the claims of current understanding of plate tectonic theory.

16.1.3 Science as Social Institution

With respect to science as a *social institution*, I have found it profitable to focus on three basic topics: (1) science and *values*, (2) science and *technology*, and (3) science and *culture*. Under "science and values," we look at epistemic values (i.e., values relating to the reliability of science as an epistemic endeavor) such as simplicity, experimental replicability, and quantifiability. We also look at ethical values, such as whether, how, and to what extent ethical values enter into scientific practices. The reading by McMullin (see Table 16.4) speaks to epistemic values directly, while the reading by Rescher focuses on the persistence of ethical values throughout the workings of scientists, from the choice of research goals to the specification of standards of proof to the dissemination of research findings. "Science and technology" spotlights how and to what extent science is related to and distinct from *technology*. Again here, looking at content, methods, and aims is useful. As Feibleman remarks, in a nutshell the aim of science is to know (i.e., to provide an understanding of phenomena), while the aim of technology is to do (i.e., to manipulate phenomena). Where science often strives to formulate *laws* or provide *explanations* and *predictions*, technology strives to create a product that does some job. Science frequently deals with abstract, idealized objects (e.g., constructing *models* using frictionless planes or mass points), whereas technology deals with more concrete

Table 16.4 Suggested readings to support the discussion of values and society

Ellstrand, N.C. (2001). "When Transgenes Wander, Should We Worry?" *Plant Physiology* 125: 1543–1545. An argument in against the use of GMOs.
Hiskes, A. and Hiskes, R. (1986). "Science and Technology: Public Image and Public Policy," in *Science, Technology, and Policy Decisions*. Boulder: Westview Press. Pages 5–33. An excellent article on the aspects of the nature of science that underlie (often tacitly) public conceptions of science and resulting public policy.
Keller, E.F. and Longino, H.E. (eds.) (1996). *Feminism and Science*. Oxford: Oxford University Press. A detailed anthology of readings on various elements of science from feminist perspectives.
Klemke, E.D. et al. (eds.) (1980). *Introductory Readings in the Philosophy of Science, Revised Edition*. Buffalo: Prometheus Books. This edited volume includes readings by Ernan McMullin and Nicholas Rescher on values within science.
Olsen, J.K.B. and Pedersen, S.A. (eds.) (2012). *A Companion to the Philosophy of Technology*. New York: Wiley-Blackwell. A rich source of articles on multiple aspects of technology, including its relations to science in terms of content, methods, and aims, as well as to technological aspects of particular sciences.
Silver, L. (2006). "Why GM Is Good for Us." *Newsweek*. March 20, 2006. An argument in favor of the use of GMOs.
Snow, C. P. (1959). *The Two Cultures and the Scientific Revolution*. London: Cambridge University Press. This is a reprint of the classic work that speaks to the perceived differences between the sciences and humanities, with Snow's efforts to bridge this divide.
Teich, A. (ed.). (2012). *Technology and the Future, 12th edition*. New York: St. Martin's Press. An anthology of readings, classic and contemporary on the nature of technology as well as social and cultural aspects of it.

objects in particularized contexts. Science and technology are not mutually exclusive domains, of course. Science relies heavily on technology (e.g., computers and sophisticated instruments), while technology relies heavily on science (e.g., theories of chemical bonding or physical forces that operate the technological products). Nevertheless, the differences are real and important. Finally, "science and *culture*" includes issues such as the politicization of science (i.e., how social and political *values* and concerns interplay with what and how scientists investigate the world), feminist critiques of science (for instance, how values such as science being neutral and disinterested in order to achieve objectivity reflect stereotypical masculine values), and C.P. Snow's important Two Cultures doctrine (namely, a sharp, perhaps even antagonistic, distinction between science and humanities). Some contemporary case studies that have been useful in my class with respect to these *social institution* aspects of science are debates about genetically modified organisms (see Table 16.4 below for useful and accessible readings).

16.1.4 Nature of Science: An Analysis of an Imaginary Case Study

These three foci of *doctrine*, *process*, and *institution* are illustrated with an opening-day discussion based on an excerpt from a classic piece entitled "*Umbrellaology*," by Somerville (1941). (Appendix features an abridged version.) This intriguing case encourages students to consider their own assumptions, presuppositions, and intuitions about the nature of science. Not only has this piece generated immediate and profitable discussion—and dissidence—in class, but also, since students see it again on the last day of the term, it has served as a useful "pretest/posttest" tool for the students' own thinking about science relative to the course and could be useful as an introduction to the nature of science as well as an assessment of students' understanding of it. After students have spent a few minutes reading the excerpt, I call for a show of hands of students who believe that *umbrellaology* is a science and those who believe it is not and ask for justifications for their positions. Students typically offer reasons for and against umbrellaology (often reasons that parallel the arguments given in the excerpt itself). Students who support the view that umbrellaology is science often put forward the following arguments:

- It is based on *observations*.
- It offers *predictions* based on those observations (hence, also employed hypotheses).
- It proposed *laws* and that, assuming the work of the umbrellaologists was unbiased and objective.
- It gave a true description of at least part of the social world.
- It was not biased by preconceived notions or *values*.

To contrast, students who argued against the view that umbrellaology is a science claimed:

- Even if it did those things, it was at best a small study within the "real" science of sociology.
- It was simply too silly a thing to study (a "who cares?" argument).
- At most umbrellaology gave a general description of some local knowledge about umbrellas, but was not universal enough.
- It offered no *explanation* for the empirical findings.

After discussion, including consideration of arguments and responses, we typically conclude that many of the claims made during the discussion appear to be based on varying views of what science is. Some views reveal a notion of science as *doctrine*, some of science as *process*, and some of science as *institution*. While the point of this exercise is not to get to "the right answer" regarding the status of *umbrellaology* as a science, students often want to know the right answer. A major goal of the course is to have students appreciate the complexities involved in identifying an endeavor as science.

Despite the justification for this case primarily as a conversation starter, it is useful to note that there are features of umbrellaology that philosophers of science would see as scientific, although few would suggest that those features definitively constitute umbrellaology as an authentic science. For example, while few current philosophers of science would claim that science can or does begin with a simple interest-neutral *observation*, a focused gathering of data is necessary for an endeavor to be considered science. Likewise, the extrapolation and subsequent testing of data, which occurs in umbrellaology, is necessary for science. However, without question, there are features of science within umbrellaology, which is why it is a useful case to foster discussion and analysis among students. What, then, are arguments against umbrellaology's claim to be science? Besides the questionable assumption of disinterested observation as a starting point for investigation, umbrellaology seems to lack any theoretical explanatory power. The only fruitful aspect of umbrellaology seems to be to provide more descriptive information.

Besides having students wrestle with their initial views on the nature of science, discussion of this case will allow the pursuit of several pedagogical and philosophical goals. First, the types of arguments presented both pro and con on the scientific status of "umbrellaology" permit the analysis of science as *doctrine*, *process*, and *institution*. Second, it easily enables the introduction of some basic elements and activities of science such as modes of information gathering and organizing, of testing and accounting for phenomena, of enhancing upon and extrapolating data, etc. Third, it helps foster a conceptual understanding of science and the understanding of the nature of science (i.e., using conceptual methods of analysis on concepts within and about science). The enunciation and appreciation of these three goals are piqued by the umbrellaology discussion, and, as a result, they are more easily met later by the incorporation of a sustained case study, namely, the debates concerning *mass extinctions* of life.

16.2 An Analysis of the Causes of Mass Extinctions: An Actual Case Study in the Nature of Science

Once students have some background in the content of the nature of science, it is useful to consider a case study both to apply the philosophical issues and analyses and also to test the philosophical claims made. A particularly effective case is that of the debates about *mass extinctions* of life on the earth. Discussion of these debates has worked well for several reasons. First, because the controversy is ongoing in the scientific community, the scientific and philosophical issues are current, the history of the debate is well established; also, students often are more engaged in wrestling with those issues than with historical cases that are resolved. Second, the underlying science concepts can be easily accessed by students regardless of their disciplines and training. This, of course, is not to say that the science is "easy," but that it can be dealt with in a way that is accessible to all students. Third, there is a wealth of material to draw from, ranging from an insider's perspective (Raup 1999), to various secondary reports and original research articles. A very useful tool to introduce the topic is "The Day the Mesozoic Died," a short video produced by the Howard Hughes Medical Institute that can be accessed on the HHMI website at the link in Table 16.4, which also features other books and articles to help students investigate this case.

16.2.1 The Extinction Debate: An Overview

Approximately 66 million years ago at the end of the Cretaceous period, the dinosaurs and other large creatures both on land and in the seas became extinct in a relatively short time geologically. By the time the Tertiary period began, the world was a very different place. With the dominant dinosaurs removed from the scene, the small mammals formally existing in the margins rapidly evolved to fill many of the niches vacated by the dinosaurs.

Many suggestions had been put forward to explain the cause for the Cretaceous extinction, but both consensus and convincing evidence were lacking. In the early 1980s, geologist Walter Alvarez discovered that a layer of clay deposited at the boundary of the Cretaceous and Tertiary periods outside the town of Gubbio, Italy, contained an abnormally high concentration of the element iridium. Extraterrestrial rocks such as meteorites were known to contain high concentrations of iridium, but few earth processes could explain the finding. In addition, a variety of quartz called shocked quartz or schistovite, which forms only under extreme pressure, was also found in the same rock layers. In collaboration with his Nobel Prize winning father, Luis Alvarez, this discovery led to the suggestion by Alvarez that the Earth was hit by a huge meteorite (Alvarez and Asaro 1990). Such an impact would have caused a dust cloud that blocked out sunlight for years, stopping plant growth, destroying the food chain, and killing off large species of animal life, including the dinosaurs.

Further work by a multitude of scientists across various disciplines—including Jan Smit, Christopher McKee, and Allen Hildebrand—led to discoveries that corroborated the hypothesis of meteoric impact. By the early 2000s, although most in the scientific community accepted the impact view, there remained some, such as Anthony Hallam, Charles Officer, and Vincent Courtillot, who were not so sure that the extraterrestrial impact hypothesis is the only, or best, viable explanation, instead suggesting that a series of volcanic eruptions could have caused the same effect while throwing iridium deep within the Earth into the atmosphere.

16.2.2 Using the Extinction Case Study: An Instructional Strategy

We first go over the historical and scientific details of the case, and I make a point of presenting the events chronologically so that students can better observe the processes of working scientists, along the lines just noted above. For example, with respect to epistemic concepts we look at the nature and role of *measurement*. Questions arise such as what exactly are the "things" that are being measured, what factors influence those measurements, how and to what extent are those measurements "theory-dependent" (i.e., that rely on prior theoretical assumptions or commitments)? With respect to conceptions of scientific *change* and *progress*, we look at questions such as whether or not the details of this case fit any particular conception better than others; for example, was the change and progress simply a matter of accumulating additional empirical information or were background paradigmatic assumptions brought into question and perhaps replaced (and, if so, which assumptions). Looking at science as a *social institution*, we consider such questions as what epistemic values seem most salient to researchers, how, if at all, has the extra-scientific community influenced actual scientific practices.

Certainly, one can use other case studies to ask the sorts of questions presented here and pursue the same sorts of goals mentioned earlier. The *plate tectonics* case mentioned, the nineteenth-century debate between the Darwinians and Lamarckians on the nature of evolution, or the debate on the possibility of spontaneous generation are all potentially useful. Nevertheless, because this specific case represents a fairly recent issue, and because it involves scientists across disciplines, and because it is accessible to students, it is particularly fruitful in terms of addressing issues in the nature of science. For an excellent discussion of various historical cases from different disciplines, see McComas and Kampourakis Chap. 30 in this volume. In addition, as noted earlier, by dealing with these issues under the rubric of science as *doctrine*, *process*, and *institution*, the various standard topics in the nature of science (such as the nature of *explanation*, the nature of *theories*, and the nature of *values* in science) make more sense to students. Consequently, students are more attuned to the importance of such topics and are more interested in pursuing them (Tables 16.5 and 16.6).

Table 16.5 Books and articles related to the mass extinction controversy

Alvarez, W. and Asaro, F. (1990) "An Extraterrestrial Impact." *Scientific American* (October), 78–84. An early argument, from a major originator of the impact view, proclaiming bolide impact as the cause of dinosaur extinction.
Boersema, D. (2009). *Philosophy of Science: Text with Readings*. Chapter 15. New York: Pearson Prentice Hall. A summary of the science and conceptual issues related to dinosaur extinction.
Courtillot, V. (1990). "A Volcanic Eruption." *Scientific American* (October), 85–92. An argument against bolide impact as the cause of dinosaur extinction.
Frankel, C. (1999). *The End of the Dinosaurs: Chicxulub Crater and Mass Extinctions*. Cambridge: Cambridge University Press. A readable overview of the science supporting and opposing bolide impact as the cause of dinosaur extinction.
Glen, W. (ed.). (1994). *The Mass-Extinction Debates: How Science Works in a Crisis*. Stanford: Stanford University Press. A collection of academic articles on the nature of science with a focus on the dinosaur extinction.
Hallam, A. (2004). *Catastrophes and Lesser Calamities: The Causes of Mass Extinctions*. Oxford: Oxford University Press. A detailed discussion of the various mass extinctions, including the dinosaur extinction, primarily arguing against bolide impact.
Officer, C. and Page, J. (1996). *The Great Dinosaur Extinction Controversy*. New York: Addison-Wesley. An argument against bolide impact aimed at a nonacademic audience.
Powell, J.L. (1998). *Night Comes to the Cretaceous*. New York: W.H. Freeman. A readable overview of the science and debates regarding dinosaur extinction.
Raup, D. (1986). *The Nemesis Affair*. (Revised edition, 1999) New York: W. W. Norton. An early argument for bolide impact and relating similar extraterrestrial causes for other mass extinction events.
Singer, M. (2011). *Extinctions: History, Origins, Causes & Future of Mass Extinctions*. Palo Alto, CA: Cosmology Science Publishers. As the title notes, a survey of the various mass extinction events and extrapolation from such past events to the future.
http://www.hhmi.org/biointeractive/day-mesozoic-died

Appendix: *Umbrellaology*: A Science or Not?

"Dear Sir: I am taking the liberty of calling upon you to be a judge in a dispute between me and an acquaintance who is no longer a friend. The question at issue is this: Is my creation, umbrellaology, a science? Allow me to explain this situation. For the past 18 years … I have been collecting materials on a subject hitherto almost wholly neglected by scientists, the umbrella. The results of my investigation to date are embodied in the nine volumes which I am sending to you under separate cover. Pending their receipt, let me describe to you briefly the nature of their contents and the method I pursued in compiling them. I began on the Island of Manhattan. Proceeding block by block, house by house, family by family, and individual by individual, I ascertained (1) the number of umbrellas possessed, (2) their size, (3) their weight, (4) their color. Having covered Manhattan after many years, I eventually extended the survey....

Table 16.6 Suggested general readings on the nature of science

Boersema, D. (2009). *Philosophy of Science: Text with Readings*. New York: Pearson Prentice Hall. This book is a hybird of a single-author text, discussing science as doctrine, process, and social institution, intersperced with exerpted readings of well-known philosophers of science. Additional case studies from the history of science are included.
Cover, J.A., M. Curd, and C. Pincock (eds.) (2012). *Philosophy of Science, 2nd edition*. New York: W.W. Norton. A standard and widely-used anthology of classic readings addressing the common areas of philosophy of science, such as observation, laws, and theories.
Godfrey-Smith, P. (2003) *Theory and Reality*. Chicago: University of Chicago Press. A single-authored text that covers standard areas in the philosophy of science. Very readable and accessible to students.
Lange, M. (2006). *Philosophy of Science: An Anthology*. New York: Wiley-Blackwell. An anthology of classic readings addressing the common areas of philosophy of science, such as observation, laws, and theories.
Machamer, P. and M. Silberstein (eds.) (2002). *The Blackwell Guide to the Philosophy of Science*. Oxford: Blackwell. A collection of single-authored essays, each focusing on detailed standard issues in the philosophy of science, such as observation and scientific explanation, but also essays on philosophy of science issues related to specific sciences, such as evolution, molecular and developmental biology, social sciences, and others.
McCain, K. (2016). *The Nature of Scientific Knowledge: An Explanatory Approach*. New York: Springer. A single-authored text focusing on the nature of scientific knowledge and how it differs from other types of knowledge.
McErlean, J. (2000). *Philosophies of Science*. Belmont, CA: Wadsworth. An examination of standard philosophy of science issues, but with a stronger emphasis than most other texts on social and cultural aspects of these issues, such as feminist and sociological approaches.
Pine, R. (1989). *Science and the Human Prospect*. Belmont, CA: Wadsworth. A single-authored discussion of the history of western science, with a strong cultural, sociological, and ethical approach.
Pitt, J. (2000). *Thinking about Technology: Foundations of the Philosophy of Technology*. New York: Seven Bridges Press. A detailed discussion of the nature of technology, including both its overlay with and its differences with science.

It was at this point that I approached my erstwhile friend...I felt I had the right to be recognized as the creator of a new science. He, on the other hand, claimed that umbrellaology was not a science at all. First, he said, it was silly to investigate umbrellas. Now this argument is false because science scorns not to deal with any object, however humble, even to the ‘hind leg of a flea.’ Then why not umbrellas? Next he said that umbrellaology could not be recognized as a science because it was of no use or benefit to mankind. But is not the truth the most precious thing in life? And are not my nine volumes filled with the truth about my subject?...When he asked me what was the object of umbrellaology I was proud to say, “To seek and discover the truth is object enough for me.” I am a pure scientist; I have no ulterior motives....Next, he said my truths were dated and that any one of my findings might cease to be true tomorrow. But this, I pointed out, is not an argument against umbrellaology, but rather an argument for keeping it up to date, which is exactly what I propose....His next contention was that umbrellaology had entertained no hypotheses and had developed no theories or laws. This is a great error. In the course of my investigations, I employed numerous hypotheses. Before entering each new block and each new section of the city, I entertained an hypothesis as regards the number and characteristics of the umbrellas that would be found there, which hypotheses were either verified or nullified by my subsequent observations, in accordance with proper scientific procedure, as explained in authoritative texts....As for theories and laws, my work presents an abundance of them. I will here mention only a few by way of illustration. There is the Law of Color Variation Relative to Ownership by Sex. (Umbrellas owned by women tend to a great variety of color, whereas those owned by men are almost all black.) …There is also the Law of Tendency towards Acquisition of Umbrellas in Rainy Weather. To this law I have given experimental verification…"

"Thus I feel that my creation is in all respects a genuine science, and I appeal to you for substantiation of my opinion."

(Excerpted from J. Somerville: 1941, "Umbrellaology" *Philosophy of Science* 8, 557–566.)

Chapter 17
Avoiding De-Natured Science: Integrating Nature of Science into Science Instruction

Norman G. Lederman, Fouad Abd-El-Khalick, and Judith Sweeney Lederman

17.1 Introduction

It has been several years since the *Next Generation Science Standards* (NGSS 2013) in the United States were unveiled, and they continue to present challenging work for science teachers. In the United States alone, there have been no fewer than three major reform documents (along with ancillary materials) in science education since the early 1990s (AAAS 1993; National Research Council 1996; NGSS 2013). The appearance of new standards in science is not limited to the United States. Similar standards have recently been unveiled in Australia, China, Germany, Sweden, and numerous other locations worldwide. The visions of these reform documents vary in many ways, but there are similarities as well. When one looks past the specific details and nuances of the various reform documents, the desired outcome has always been scientific literacy, a perennial goal of science education (NSTA 1982).

Science is one of many ways of knowing and its focus is primarily on understanding the natural world. But knowing the laws, theories, concepts, and big ideas in science textbooks, as well as how these types of knowledge have been developed, is not enough. Rather, we want all citizens to be able to use their knowledge of science to make informed decisions about personal and societal issues that are grounded in science and to engage in scientific discussions that are of importance globally and locally.

Science as a way of knowing is difficult to define beyond statements about its general purpose or goals. One straightforward way to think about science is to con-

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_17

sider it as having three basic components. First, science consists of a body of knowledge. Second, there are the processes and strategies for the development of the knowledge (i.e., inquiry/practices), and third, there are the characteristics of the knowledge that are directly and necessarily derived from how the knowledge is developed (i.e., nature of science). Obviously, these components of science are intimately related. Knowledge is developed using inquiry/practices and the resulting knowledge has specific characteristics that are derived from the manner in which the knowledge was developed (Lederman and Lederman 2014).

With respect to achieving the goal of scientific literacy, most science educators have realized that knowledge of how scientific knowledge is developed and the characteristics of the knowledge that are engendered by the development of the knowledge are critical to the informed decision making (NSTA 1982). Everyone must be able to weigh the claims made by scientists and understand the inherent limitations of scientific knowledge. Students' understandings of NOS and SI, and how together they support the attainment of scientific literacy, remain as inadequate as they have been since the 1960s (Lederman 2007).

The US *Next Generation Science Standards* (NGSS Lead States 2013) are organized into three dimensions (i.e., Disciplinary Core Ideas, Science and Engineering Practices, and Crosscutting Concepts). Understandings about nature of science (NOS), which also includes what was formerly known as knowledge "about" scientific inquiry (SI), are generally linked to statements with the dimensions of Science and Engineering Practices and Crosscutting Concepts. As important as inquiry and nature of science were considered as components of scientific literacy in previous years, neither the Benchmarks or NSES was successful at getting this message understandable to most students. In short, NOS refers to the characteristics of scientific knowledge that necessarily result from the conventional approaches (i.e., scientific inquiry) that scientists use to develop knowledge.

NOS statements related to the use of a variety of shared methods, the role of evidence, and the notion that science addresses questions about the natural world, science is a way of knowing, and science is a human endeavor are clearly found in Appendix H of the NGSS. Teachers will most likely not consult the appendix but will find many of NOS statements linked to the Science and Engineering Practices and Crosscutting Concepts on each page of the standards themselves.

We find that some statements such as science are a "way of knowing" and science is a "human endeavor" as too broad and vague to be of much instructional use. More useful for the teacher is that these characteristics include aspects of NOS such as scientific knowledge is subject to change, and is a function of human creativity/imagination, subjectivity, and necessarily includes both observations and inferences. Students' understandings of NOS and SI, and how together they support the attainment of scientific literacy, remain as inadequate as they have been since the 1960s (Lederman 2007). However, empirical research in the past three decades has clearly indicated that students' and teachers' learning about these critical areas was best facilitated through an explicit, reflective approach to instruction (Bell et al. 2003; Lederman and Lederman 2014).

The focus of this chapter is to provide concrete examples of how to facilitate students' understandings of NOS within the science curriculum. That is, the activities and experiences provided are not "standalone" activities focusing on NOS, but rather examples of how NOS can be emphasized within instruction that addresses scientific concepts and processes, within the disciplines of biology, chemistry, physics, and earth science. In short, the activities are not decontextualized. They are all embedded in the teaching of the science content specified in typical science curricula. This chapter is a new and revised version of the chapter written in a previous version of the current text (Lederman and Abd-El-Khalick 1998). Some of the activities/experiences are the same, but some are new. We highly recommend that you consult the previous chapter because the two together provide a much more comprehensive NOS resource.

As far as communicating proper understandings of the NOS to students is concerned, teachers have been led to believe that their students will come to understand NOS simply through the performance of scientific inquiry and/or investigations. This is no more valid an assumption than expecting that students will learn the details of cellular respiration by watching an animal breathe. Consequently, NOS is explicitly emphasized in each of the following activities/experiences as are the more traditional science concepts targeted.

17.2 About the Activities and Experiences Presented Here

This chapter introduces a set of activities/experiences designed to model an explicit approach to teaching science subject matter as well as crucial aspects of NOS. These activities have been successfully used with elementary, middle, and high school students as well as preservice and inservice teachers. Those interested in helping students learning about NOS can use the following activities to convey adequate understandings of NOS to students and teachers. The NOS aspects advocated in these activities/experiences are designed at a level of generality and developmental appropriateness that renders them virtually noncontroversial. That is, highly esoteric aspects of NOS that are developmentally inappropriate and unconnected to the common K-12 school curriculum are not included. For example, philosophers can successfully argue that there really are no true observations, just inferences. However, this esoteric notion is well beyond the reasonable comprehension of a seventh-grade student when they are looking at a chair or anything seemingly tangible.

Science educators can use these activities in either science courses or science teaching method courses. If the audience consists of precollege students, the appropriate grade level(s) for using a certain activity/experience are pointed out, but most can easily be adapted for audiences of varying levels of sophistication. Where appropriate, extensions that make an activity/experience more amenable for use with older students are included.

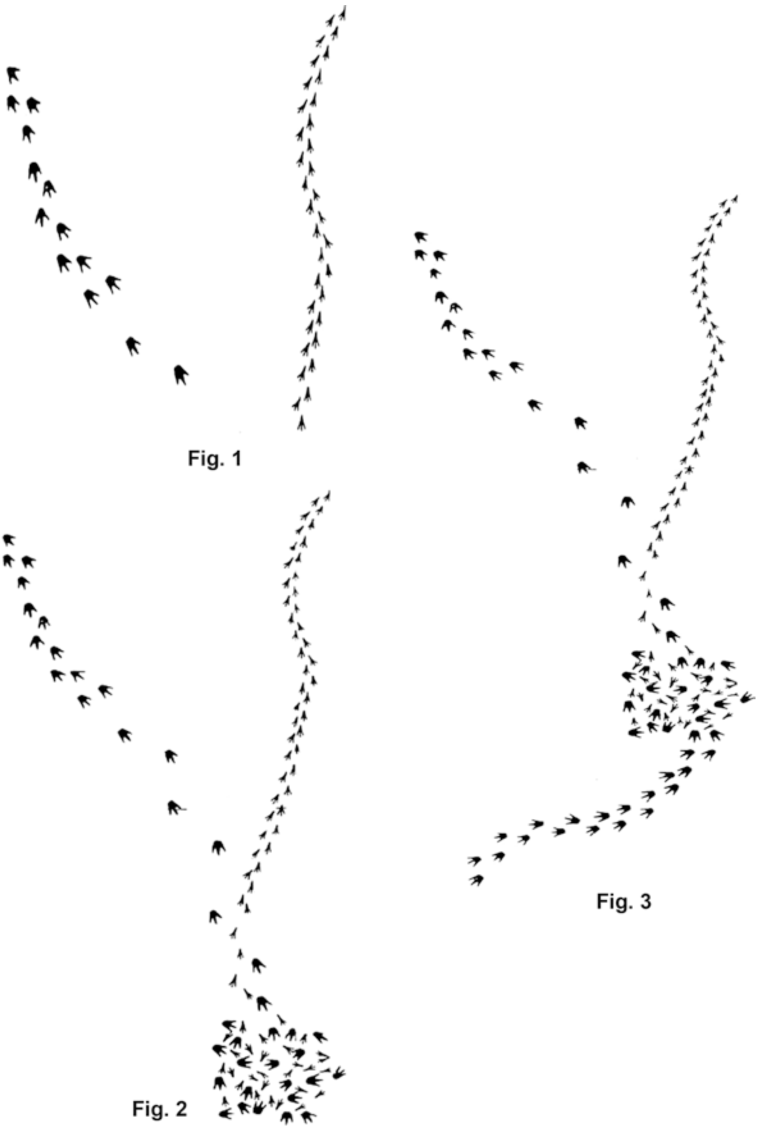
Each activity/experience specifies what students can learn, materials, setup, and/or procedure as well as a possible instructional scenario. The PowerPoint™ slides that are needed for the activities and experiences can be conveniently reproduced from the images included. The instructional procedure/scenario section provides an explicit idea about the kind of questions and answers that can be expected and the aspects of NOS that need emphasis during a certain activity/experience. These scenarios are not meant to be prescriptive in any respect. Rather, they are drawn from classroom experiences and genuine student reactions and are meant to provide a better idea about one possible discourse among many equally fruitful classroom interactions. The approach taken for a certain activity/experience is up to the professional judgment of the teacher.

17.2.1 Tricky Tracks

This activity is easily embedded within a biology unit focusing on fossil evidence or with an earth science unit focusing on fossils. When dealing with fossils, it is important for students to not only know how fossils are formed, but also how scientists use fossils to make inferences about structures, organisms, and events that existed or occurred many years ago. "Tricky Tracks!" conveys to students the message that every idea is important irrespective of it being the "correct" answer. Students completing this activity will gain experience in distinguishing between observation and inference and realize that, based on the same evidence (observations, or data), several answers to the same question may be equally valid.

Grade Level: Any
Materials: Create Separate PowerPoint™ slides of Figs. 17.1, 17.2, and 17.3.
Targeted NOS Aspects: tentativeness, subjectivity, observation, inference, empirically based
Discipline: Biology, Earth Science
Instructional Scenario:

1. Show students Fig. 17.1 and tell them that a group of scientists came upon this set of footprints on the ground. Ask the students to volunteer their ideas about what they are observing. As students offer their observations and inferences gathered from Fig. 17.1, list these on the board.
2. Ask students questions such as, "What kind of animals left these footprints?" "Are the two animals of the same type, but of different size or are they different types of animals?"
3. Ask students, "In which direction are the animals walking?" Then students defend their inferences.
4. Students will readily (without much prompting) offer their ideas of what is happening (by making inferences). When this occurs, ask students if they directly observed one animal seeing the other and walking toward it. You can



Figs. 17.1–3 Two partial (Figs. 17.1 and 17.2) and the full set (Fig. 17.3) of Tricky Tracks. We recommend showing students Fig. 17.1 (upper left), then Fig. 17.2 (lower left), and finally the entire set of tracks (right). It will be most effective to produce three PowerPoint™ images and reveal the tracks on set at a time

tell students these are inferences, or you can ask them about the difference between seeing the footprint and deciding that one animal sees the other and is walking toward it. Follow this with a discussion about the difference between observations and inferences and ask students if making observations and inferences are something that scientists do.

5. As the discussion proceeds let students offer their inferences of what happened. Let students "debate" with their classmates about the reasonableness of each of the inferences made. Students will weigh the merits of the various inferences.
6. You can increase the discussion and help students to think further about what is occurring by asking why the footprints of the larger animal are not consistently the same distance apart. This will typically result with students converging on the idea that one animal (students typically think it is a bird) sees the other and starts to run toward it. Help students to question this idea by asking if there is another reason that footprints get further apart other than running or walking faster.
7. On the board, continue to list students' observations and inferences gathered from Fig. 17.1.
8. Now show Fig. 17.2. Again, ask students what they see and what they think has happened. Some students will change their inferences about what they saw in Fig. 17.1 and others will see the additional data as confirming their initial ideas.
9. Students will typically make the following inferences:
    (a) One bird saw the other and ran toward it as a predator.
    (b) The birds are mating.
    (c) The birds are both eating something.
10. Accept all answers at this point and avoid making any judgment. As much as possible, you want students to use the observations to make inferences that they feel they can defend. Point out to them that they are doing what scientists do when they collect data and draw inferences.
11. As the discussion begins to wane, show Figures 17.1, 17.2, and 17.3. As previously done, have students make observations and inferences and defend their inferences. Again, avoid making judgments. After all, these events happened in the past and there is no way to actually know what happened. The students (just like scientists) are making inferences from the observations and from what they already know.
12. Typically, once Fig. 17.3 is shown, the following inferences will likely be offered by students:
    (a) One bird killed the other.
    (b) One bird flew away.
    (c) The larger bird was a parent, and he/she picked up the younger bird, and put he/she on its back or in its mouth and walked away. Throughout the discussion, be sure to have the students distinguish between their observations and inferences.
13. Once the students have settled on one to three inferences about the events, it is interesting to get them thinking a bit more by asking them, "Why is every-

one assuming the footprints were made at the same time?" Maybe the two birds were not in the same location at the same time. This will lead to another set of inferences.

14. Throughout the discussion students should be asked if they have changed their ideas and why, and "Why, even though everyone was looking at the same data, different inferences were made?"
15. As you can see, the directions the class discussion may follow are endless. However, the ideas that scientific knowledge is tentative (subject to change), involves human creativity, is necessarily subjective, is based on observations and inferences and investigations can follow a variety of approaches can easily be emphasized. These characteristics of scientific knowledge and practice can easily be elicited from students (although they may use different words). That is, students can develop conceptual understandings of these aspects of NOS without being directly told the aspects by the teacher.

    The crucial point to remember is that this activity integrates these NOS understandings seamlessly into science instruction about fossils rather than just teaching about NOS without a science content context and how they can be used within scientific investigations about historically earlier events. The activity is not designed to stand alone only to teach about NOS with no science context.

17.2.2 Core Sampling and the Construction of Topographical Survey Maps

This activity/experience provides a concrete way for students to understand how scientists infer what types of rock layers exist below the surface of the land we observe. In addition to teaching important science processes and geological concepts, it is also a perfect platform for emphasizing certain aspects of NOS, in particular, students' understanding of observation and inference in science and the notion of creativity and its role in constructing scientific knowledge. After completing this activity, students should be able to appreciate that scientific knowledge is partly a product of human inference, imagination, and creativity, even though it is, at least partially, also supported by empirical evidence. Moreover, students will come to realize that science does not produce absolutely certain knowledge. All scientific knowledge is subject to change (i.e., tentative) as more evidence is accumulated or as already available evidence is reinterpreted in light of newly formulated hypotheses, theories, and/or laws.

Level: Upper elementary and middle school

Materials: One manila file folder, a sheet of construction paper that will fit inside the folder, one acetate sheet (per student or group of students). See instructions for creating this below. Paper sheets of assorted colors, adhesive tape, glue. Sample geological survey maps from various locations.

Targeted NOS Aspects: tentativeness, subjectivity, observation, inference, empirically based

Discipline: Earth Science

Teacher Preparation: On the large or tab side of the manila file folder, punch several holes randomly (Fig. 17.4). It may be necessary to cover the folder with an opaque material (e.g., white opaque paint) to prevent seeing the shapes in the folder. Next, tape the folder leaving the tab end open creating an envelope (Fig. 17.5). Create an insert by gluing differently colored, randomly shaped pieces of paper to a sheet of construction paper (Fig. 17.6). The inserts need not be the same for all prepared folders. Insert the construction paper into the envelope with the colored pieces of paper facing the holes (Fig. 17.7).

At this point, tape an old overhead transparency (or sheet of clear plastic) over the side of the folder with the holes. With a nonpermanent pen, students can draw on the transparency and erase their drawing.

Instructional Scenario:

1. Tell students that they will be engaging in a situation like what scientists do when they are trying to determine what types of rocks are below the visible surface of the Earth.
2. Hand each student, or group of students, a manila folder (with the insert inside) and an erasable or nonpermanent pen. The erasable pens allow you to re-use the folders in other or future classes.
3. Inform students that the inserts have certain colored shapes glued to them. Without removing the inserts, students need to figure out those shapes and colors. The only available information to the students is what they see of the colored paper through the holes.
4. Have students trace their proposed shapes on the overhead transparency.
5. When your students finish their proposed shapes, take the time to make explicit the similarities between what they are doing and what scientists usually do. Faced with a natural phenomenon (the insert), scientists pose certain questions to which there usually are no readily available answers – What is

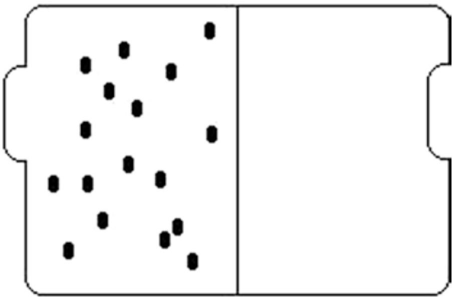


Fig. 17.4 Open file folder (left) with randomly spaced holes on one side

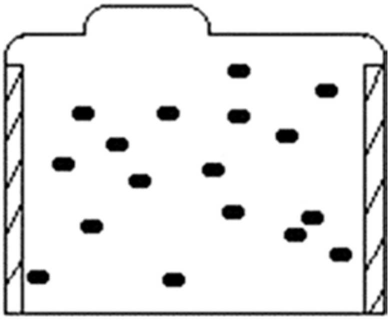


Fig. 17.5 Closed file folder (right) with sides taped shut so that the sheet shown in Fig. 17.6 can be slipped into the open top

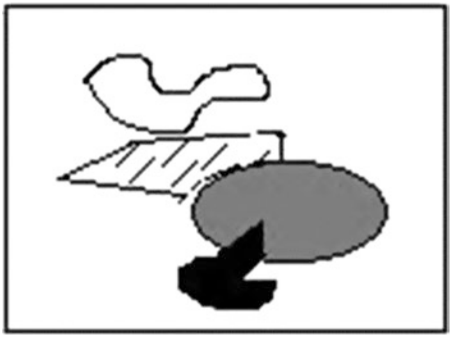


Fig. 17.6 Illustration (Left) showing the construction paper shapes glued to the insert that will be slipped into the open top of the file folder

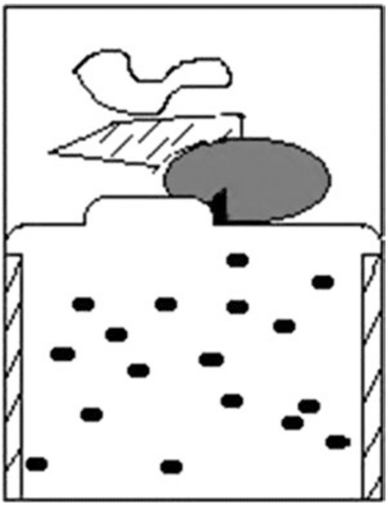


Fig. 17.7 Illustration (Right) of the insert being placed into the file folder

the shape of the colored pieces of paper on the insert? The activity aims to put students in a situation similar to the ones that geologists face when constructing geological survey maps. Just like your students, scientists would rather handle the phenomenon first hand, which in the present case would be to simply pull out the insert and see how it looks. This, however, is rarely possible.

For example, for a few 100 years, physicists theorized the presence of atoms, formulated many atomic theories, investigated the structure of the atom, and accumulated a great deal of knowledge about the atom and its components. This knowledge in turn has allowed many advances in physics and related fields. All of this occurred even though scientists never saw atoms directly. (It is true that using super-accelerators/super-colliders physicists could break atoms into smaller pieces. However, another problem of "visibility" arose. The now-famous "Higgs" particle seems to "block the vision" of scientists who again seem not able to "see" what they would like to see firsthand). In a similar fashion, astrophysicists have produced scientific knowledge about the inside of the sun and the kinds of reactions taking place within, all without splitting the sun open!

6. The question arises, "How do scientists produce a seemingly reliable body of knowledge about such phenomena?" Scientists collect data about the phenomena they study. The holes on the folder represent data points (i.e., core samples) allowing us to view a part of the object of investigation. The data points that can be collected about different phenomena vary in several ways. Some of those ways include the:

    - Amount of data (e.g., number of holes) which may depend on the feasibility and the practicality of collecting the data. For example, in geological surveys, it is possible, but not at all practical, to collect rock samples from every square meter of terrain. Samples are usually collected from a much larger unit area.
    - Quality (such as small versus larger holes) which relates to the accuracy, precision, etc. of the data. The quality of data depends on a multitude of factors. Technology is one. For example, the quality of the Hubble telescope photos of distant galaxies now available to astronomers is by far more informative than earlier photos taken by observatories on Earth.
    - Availability (e.g., it may not be practical for us to indefinitely punch holes in the folder to see the whole insert below). For example, astrogeologists would certainly like to examine every meteorite, but they can only hope to locate some of the meteorite samples available on Earth.

7. After collecting data, scientists, will infer answers – as your students did – to their questions consistent with the data. Creativity and imagination are essential to this process. In much, the same way that your students have literally filled in the gaps between the holes to generate a final picture of what they thought the colored pieces of paper look like, scientists engage in a

creative process to make sense of the data they have collected and come up with a final picture or an answer.

8. Ask a few of your students to remove the insert from their folders (other students should keep their inserts inside). Ask those students to compare, in front of the class, their proposed drawings with what the inserts actually look like. If you were careful to glue randomly shaped pieces of paper to the insert, your students will be surprised with the differences. Point out that scientists, very often, are not able to "pull out their inserts and examine them." Rather, they must infer an answer from the available data.
9. Hand out geological survey maps from the United States and Canada. Each group should get one map from the United States and one from Canada. Have the students investigate the color coding for different rock layers on the two maps. Ask students to describe any differences they notice.
10. Students will quickly notice that on the United States maps each rock layer is represented as a homogeneous color, while on the Canadian maps each rock layer is a combination of a lighter and darker shade of the same color. Ask students what they think the lighter color represents (what has been inferred) and what the darker colors represent (what has been observed in the field through outcroppings and core sampling).
11. Ask students to draw analogies between the maps and the folders. The discussion should result in students' explaining that the holes in the folders are analogous to actual observations or outcroppings and the parts that they drew on the acetate sheets are analogous to the inferred parts of the survey maps.
12. Ask some of your students whose inserts are still inside their folders how certain they are about their proposed drawings! Ask your students whether they think scientific knowledge can be absolute or certain. (A good discussion usually results). With older students, it might be a good idea not to permit them to remove their inserts. This provides an experience that is more consistent with actual scientific investigations. With younger students, you might let all of them remove their inserts, especially if they show signs of frustration. (In most cases, scientists do not stop at the initial phase of collecting and inferring as was the case with this folder activity. Rather, they then derive predictions based on their hypothesized answers and test those predictions by collecting more direct or indirect data. This aspect of NOS is dealt with in following activities.)

In summary, this activity helps develop students' understandings of the work of geologists as they attempt to map the layers of the Earth, as well as help students develop understandings of important aspects of NOS.

17.2.3 Doing Real Science with Real Fossils

This activity/experience helps students realize that scientific knowledge is partly a product of human inference, imagination, and creativity. The advantage of this activity is that students work with the same artifacts and data (i.e., fossil fragments) as paleobiologists. In addition to helping students develop informed understandings of NOS, this experience will assist students in their understanding of the relationship between structure and function of organisms and how organisms are adapted to their environment.

Level: Upper elementary through High school

Materials: Fossil fragments (not complete fossils), construction paper, scissors (per student or pair of students). Depending on where you live, fossil fragments can be gathered at the beach, purchased from a science supply company or borrowed from the zoology department of a local university or museum.

Targeted NOS Aspects: tentativeness, subjectivity, observation, inference, empirically based

Discipline: Biology

Instructional Scenario:

1. Give each student (or pair of students) a fossil fragment (examples may be seen in Fig. 17.8) and ask them to make a detailed diagram of it. The diagrams may be larger than the actual fragments, but students must include the appro-

Fig. 17.8 Representative fossil fragments that may accompany this activity

Fig. 17.9 Image of the original fossil fragment

priate scale with their diagrams. If possible, provide students with sets of similar or identical fossil fragments so that different student groups can compare their inferences at the end of this activity.

2. Ask students to trace the outline of their fossil fragment on a separate sheet of colored construction paper. This tracing is cut out, and the inside is discarded to form a window so that when the construction paper border is placed over the paper containing the fossil fragment diagram, only the diagram appears.
3. With a different colored pencil, instruct students to complete their fossil drawing (to scale) on the construction paper containing the fossil fragment diagram. Students should end up with a drawing of an organism from which they believe the fossil fragment has come. This drawing task can occur in class or be assigned as homework.
4. The result of the previous steps is that each student ends up with a complete fossil drawing with two parts: the original fossil fragment drawing in one color and the inferred drawing of the complete organism in another color.
5. Ask students to staple together the construction paper with the previously cut window and the paper with the complete drawing. The papers should be stapled on one side such that they can be flipped open. The fossil fragment diagram should only show through the construction paper window. This format enhances the presentation of the original (fossil fragment) and completed diagrams to other students (Figs. 17.9 and 17.10).
6. Ask students to make an oral presentation in which they describe the habitat, diet, behavior, and other characteristics of the organisms they have extrapolated from the fossil fragments. Ask whether the students knew in advance what organism their fossil fragment came from (e.g., coral). Ask those students whether their prior knowledge affected the inferences they made about the habitat, diet, etc. of the complete organism that they inferred from the fossil fragment. This is a good time to make the point that that scientists' prior

Fig. 17.10 View of the completed fossil diagram

knowledge often influences their interpretations of the data and affects their conclusions.

7. If fossils from the same organism were assigned to several students, have students compare the organisms that different students inferred from these similar or identical fossil fragments. If the inferred organisms were different, ask students: “Can we tell for certain from which organism the original fossil fragment come?” Also ask, “How can two students looking at almost identical fossil fragments develop very different “complete” organisms?”

   Explain to students that we might not be able to give a definite answer. Continue by asking: “Is it possible that scientists face a similar situation?” “Can scientists differ in the inferences they derive from data?” “If yes, how can such differences be settled?” Explain to students that all too often scientists may reach differing conclusions based on the same evidence, just as the students have done in this activity. Provide some contemporary examples that come from current debates in the scientific community. Scientists also often hold their views strongly and do not give them up easily.
8. Make it explicit to students that what they have done is very similar to what paleobiologists and other scientists who investigate fossils do. Point out that creativity is involved in extrapolating or inferring from fossils the kind, habitat, and lifestyle of the organisms whose fossils or fossil fragments are investigated.
9. Conclude this activity by talking about the famous case of the dinosaur Iguanodon. When it was first reconstructed, the thumb was originally placed as a spike above the nose! It is useful to remind students that any reconstruction should be considered tentative – just like all the products of science.

17.2.3.1 High School Extensions

Initiate a discussion about the extent to which creativity plays a role in science with the case of hominid evolution. Tell the story of the evolution of humans over the course of the past five million years. Scientists have formulated several elaborate and differing story lines about this evolution. It is noteworthy that all that is available to those scientists is a few teeth, tools, and parts of skulls and skeletons! Inference, imagination, and creativity serve to fill in the gaps, which in this case seem to be enormous!

The same discussion can be carried further to introduce students to the notion that scientific knowledge is affected, to varying degrees, by the social and cultural context in which it is produced. The different story lines in the above example about the evolution of humans were heavily influenced by social and cultural factors. Until recently, the dominant story was centered about "the man-hunter" and his crucial role in the evolution of humans to the form we now know (See Lovejoy 1981). The hunter scenario was consistent with the white-male culture that dominated scientific circles up to the 1960s and early 1970s. As the feminist movement grew stronger and a female voice appropriately emerged in the narrative about human evolution, the story about hominid evolution changed. One story more consistent with a feminist approach is centered about "the female-gatherer" and her central role in the evolution of humans (see Hrdy 1986). It is noteworthy that both story lines are consistent with the available evidence.

Scientists are often portrayed as being totally objective. As they engage in their work, scientists are thought to set aside their personal prejudices, perspectives, and beliefs.

This objectivity, among other things, is believed to allow scientists to:

- Conduct "objective" observations. Scientists make theory-free observation. They simply describe and measure things as they are. These observations are independent of what the scientists know, believe, or how they view the world.
- Reach "objective" conclusions. Based solely on their objective observations, scientists use the rules of logic and inference to formulate hypotheses or theories to explain the phenomenon under investigation.
- Evaluate new evidence objectively. After they formulate an idea, scientists collect more evidence to test the adequacy of these ideas or to test their predictive power. Hypotheses and theories are "objectively" evaluated against this evidence. Confirmatory evidence tends to strengthen the hypothesis or theory and eventually leads to its acceptance by scientists. However, if the hypothesis or theory is not supported by the evidence, it is rejected.

It may be tempting to accept the above claims, but this history of science, however, is full of instances that counteract each of them. It is often the case that scientists interpret the same evidence differently, formulate different hypotheses to explain that evidence, and fiercely defend those explanations or hypotheses. In fact, controversies are commonplace in science. Notions of high levels of objectivity have been discounted by many philosophers and historians of science.

For instance, Kuhn (1970) suggested that all scientific observations and interpretations are in some respect subjective. Kuhn advanced the notion of "paradigm" to account for what usually happens in science. A paradigm defines, for a certain research community, the phenomena that are worth researching, acceptable questions to ask of those phenomena, appropriate research methodologies, adequate instrumentation, and the relevant and admissible evidence. For a scientist, a paradigm acts as a lens through which his/her observations are filtered. In a sense, the interpretations and explanations that a scientist formulates are consistent with that paradigm.

Although you may not want to formally introduce your students to all the above notions, certain ideas are worth emphasizing to your upper middle and high school students. Scientists' beliefs, previous knowledge, training, experiences, and expectations all combine to influence the work of those scientists. All these background factors form a mindset that affects what scientists observe (and don't observe) and how they make sense of or interpret their observations. It is this individuality that accounts for the role of subjectivity in the production of scientific knowledge.

17.2.4 Construction of a Model of the Atom (Also known as, The Mystery Tube)

There are numerous situations in science in which theoretical models are developed from incomplete data and the resulting model has never actually been seen (e.g., the center of the earth, an individual atom). Students of all ages have a difficult time understanding that many of the pictures in their science textbooks are not exact mirrors of reality and that scientists often infer scientific knowledge from the incomplete data they possess. This is certainly true of the model of the atom.

The following activity/experience is perfect for a chemistry class or any class that investigates the structure of the atoms and how they behave. In addition to learning about the structure of the atom, the activity can also facilitate students' understandings that scientific knowledge is tentative, involves subjectivity, and is necessarily a function of observations and inferences, among other aspects of NOS.

Grade Level: Any
Targeted NOS Aspects: tentativeness, subjectivity, observation, inference, empirically based, theory/law
Discipline: Chemistry, Biology, Physics
Prerequisite knowledge: None
Model Construction: Individual students
Materials: 1 tube (mailing tube, core of toilet paper role, or PVC pipe, approx. 30 cm), 1 plastic ring (optional, you can simply loop the lower rope over the upper rope), rubber stoppers or tape (to seal tube ends), 1 roll of clothesline rope

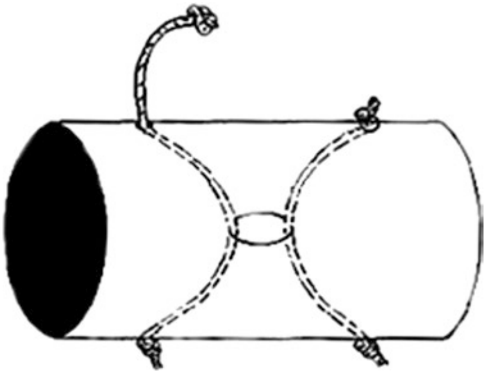


Fig. 17.11 The construction of the mystery tube. Students see only the knotted ropes that appear on the outside of the tube

(for whole class), 1 toilet paper roll core or other cardboard tube (these can be provided by the students) (Fig. 17.11).

Instructional Scenario:

1. Begin class by having students look at a picture of an atom. (This could be an image from a textbook, online source, or handout.) Ask, "How do scientists know what an atom looks like?" Most students will answer with a comment about some version of a microscope or electron microscope. Then, tell the students that no one has ever seen an individual atom. Allow them to respond to this fact or immediately move to your demonstration of the "mystery tube."
2. Hold a preconstructed tube in front of the class and asking various students to provide one observation. Be sure not to let the students pull any of the ropes or open either end of the tube.
3. As observations begin to wane, help students by directing their attention to certain parts of the tube. For example, it is a good idea to use rubber stoppers that contain one or more holes to cover the two ends of the tube. Students will not initially look at the stoppers carefully.
4. It is typical for students to quickly begin speculating about what is inside the tube. When this occurs, be sure to state that you are only asking for observations not inferences. Ask them why discussing what may be inside the tube is an inference.
5. After about 10 min of observations, ask students to observe carefully as you pull on various ropes. Ask students what they predict will happen when a rope is pulled.
6. Begin by pulling on one of the ropes at the top end and after the opposite side rope moves inward, do the reverse. This is not interesting to students because the predicted results and actual behavior of the ropes are intuitive.
7. Now begin pulling various ropes in any order you desire and the students will see behaviors that are not predicted. This will create much interest by

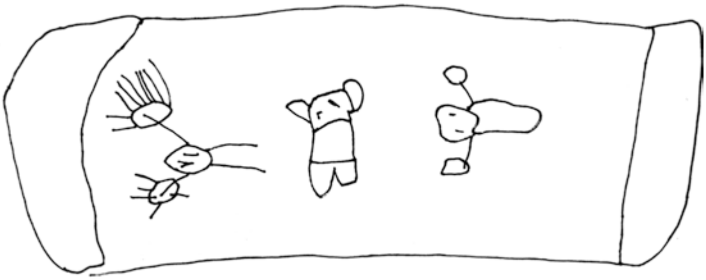


Fig. 17.12 A student's serious or not-so-serious inference about the contents of the tube. (Redrawn from the original)

the students and they will start speculating about what is inside the tube to explain what they are observing.

8. Have students, individually or in pairs, drawn a model of what they think is inside the tube that would explain the data that they have collected/seen on a sheet of paper.
9. Let the students suggest new ways to manipulate the ropes (e.g., pulling half way). As you follow their requests, ask the students if any of their ideas have changed and if so, why?
10. At this point there should be a variety of different ideas about what is inside of the tube.
11. Ask a few students to draw their models on the board. Continue until all possible models are exhausted. You will likely get about four to five different ideas. On occasion, you may get an inference that looks like the one below (Fig. 17.12), drawn by a third-grade student.
12. A proposal such as this will inevitably result in laughter from other students, but this is an important teachable moment. Ask the students why they are laughing. The responses will focus around the idea that no one has ever seen a person this small or the answer makes no sense given what we know. This can be used to stress to the class that not all inferences are equal. Inferences from data must be consistent with the data and what we already know about the world.
13. Ask the students: "If we are all looking at the same thing, why are there different ideas?" This will lead to a discussion about how students are all different and have different interpretations. Ask students, "Is this situation the same as with scientists?" Ask why they think so. Stress how subjectivity and creativity always surface when scientists are interpreting data. Ask, "How do we find out who is right?" Students will ask you to open the tube, but you should respond that the tube is like the world, you cannot open it up to see what is inside or like the atom we are not yet capable of seeing.
14. Other suggestions will be made, but wait until someone suggests that each student makes their own tube. Ask students what this would accomplish. They will readily say they are testing their ideas. You can relate this to what they were doing when they were asking for certain manipulations of the

ropes. Remind the students that they are doing exactly what scientists do when they investigate phenomena.

15. Next, in class or at home, have students make a physical model of their drawings. If students do this in class, you can provide them with the inside core of a roll of toilet paper, string (instead of rope), and whatever else you want. But keep in mind that the students will try to incorporate whatever materials you provide.
16. After all students have completed their tube model, have the students pull the same ropes that you pulled to see if their model works the same as yours. You will inevitably have several different student models behave in the same manner as yours.
17. Ask the students this very important question, "If your model works the same as mine, do you know what is inside my tube?" It will not take long for students to conclude that the answer is "no" because several different models work the same as yours. At this point, you can stress that in science, inferences are made based on data and different scientists may interpret the data differently, just like they did.

    Furthermore, the inferences that scientists make about the structure of the atom (or what is in the tube) involve human creativity and are necessarily subjective to some degree.
18. The vital job for the teacher is to help students make the transition from the tube, with ropes extending out of it to the science of chemistry. Have the students recall what was discussed at the beginning of the lesson about atoms. That is, there is a picture in the textbook of an atom, yet no one has ever seen an atom. The ensuing discussion should elaborate on the analogy between what the students did with the tube model and what scientists have done to determine what an atom looks like. The discussion should focus around how the development of scientific knowledge (or what students think is in the tube) involves human creativity, is necessarily subjective and tentative, and is based on observations and inferences.

    Note that this very well-known activity created by Norman Lederman in the 1980s has often been misinterpreted to be a context-free activity. This interpretation is incorrect. Who would do such an activity and not have it relate to the subject matter students are expected to learn? The activity can be referred to throughout the year whenever students are learning about science models or ideas that have not been directly observed, but inferred.

17.2.5 The Power and Pressure of Air

Air pressure is a very challenging concept for students to understand because students have difficulty understanding how something they cannot see can exert pressure and move other forms of matter. This activity is appropriate for introducing air pressure in a biology or chemistry class. It can be used to teach about air pressure and its interaction with other forms of matter, and represents a unique way to help

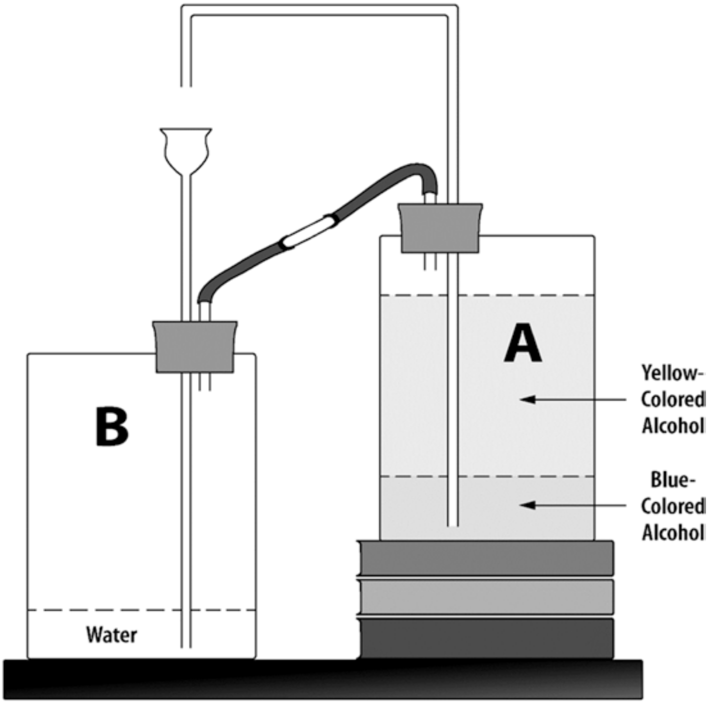


Fig. 17.13 Details of the construction of the demonstration. (Shown as if the cans were transparent)

students understand that scientific knowledge is tentative, a function of observation and inference, involves creativity, and is empirically based.

Grade Level: Middle and High School

Targeted NOS Aspects: tentativeness, subjectivity, observation, inference, empirically based

Discipline: Biology, Chemistry

Prerequisite Knowledge: Introductory knowledge of pressure (liquid and air)

Materials: Two empty metal cans (available in the paint section of many building supply stores, two rubber stoppers, rubber tubing, one thistle glass tube funnel, glass tubing, ethyl alcohol, and food coloring).

Constructing the Demonstration: The initial levels of liquid in cans “A” and “B” are shown in Fig. 17.13. Can “B” contain plain tap water. Can A contain a tap water colored with blue food coloring at the bottom (about 1/3 of the can), and the rest of the can is filled with ethyl alcohol dyed yellow with food coloring. When adding the yellow-colored alcohol, do this slowly to prevent any unnecessary mixing or agitation. A small segment of glass tubing should be inserted within the rubber tubing that connects cans “A” and “B”.

Instructional Scenario:

1. Begin class by having the students make observations of the demonstration setup (Fig. 17.13). Have students offer observations of every aspect of the setup. For example, they might say things like “Can A is higher than Can B,” “A tube connects the two cans,” or “Each can has two tubes entering it.”
2. Begin the demonstration by pouring a red-colored liquid from a reagent bottle labeled with a “bogus” chemical formula (e.g., CH2H704) into the thistle tube. The red liquid is nothing more than tap water colored red with food coloring.
3. Pour enough liquid into the thistle tube until a blue liquid starts flowing out of Can A and into the funnel inserted into Can B. The water will keep running for approximately 20 min. If the flow stops pour more of the red liquid into the thistle tube to restart the flow.
4. Initially, blue-colored water will flow from Can A to Can B. This will eventually turn into a green color at the interface of the blue water and yellow alcohol, and finally into a yellow-colored liquid.
5. As the demonstration proceeds, ask students, in groups, to explain what they see and then to offer inferences about the original contents of the cans and how far each glass tube extends into each can.
6. Students can be invited to the front of the room to look at the cans more closely.
7. After students have speculated about the contents of the cans at the start of the demonstration, ask if there is anything they want you to do to the apparatus. As students make suggestions, discuss that what they are really doing is testing their hypotheses, just as scientists would do. Typically, students will ask you to squeeze some of the rubber tubing, lower Can A to a level beneath that of Can B or squeeze either can.
8. Have students record their conclusions, which should include the initial contents of each can, how far each glass tube extends into each can, and an explanation for both the continuous flow of water and noted color changes.
9. Students typically conclude that the red liquid created a chemical reaction in Can B, which then liberated a gas. This gas traveled to Can A and then chemically interacted with the liquid in Can A to change its color.
10. As the discussion proceeds, the teacher can emphasize how the pressure of air in the cans changes and how air pressure, or any pressure in a gas, can provide enough force to move liquids or solids if the liquids or solids are between a pressure gradient. That is, air moves from high pressure to low pressure and if there is a solid or liquid between the two pressures enough force can be created to move the liquid or solid. Ultimately, after discussion, students should understand that the flow of liquid was caused by changes in air pressure within the cans. Students usually do not arrive at the idea that the color change was unrelated to a chemical reaction.
11. In addition to teaching students about air pressure and its potential effects, this demonstration also provides the opportunity for the teacher to ask students to reflect on the nature of the scientific knowledge created (i.e., the model about the contents of the cans). This activity can help students under-

stand that scientific knowledge is tentative, that their models were a function of their own creativity and subjectivity, as well as their prior knowledge. For example, ask students how their models were a function of their own creativity and to reflect on the observations and inferences they made that were a focal point of the lesson.

17.2.6 Mystery Bones

This activity/experience takes 3–4 days (depending on students' grade level) and is ideal for introducing skeletal systems within a biology or life science course. The overall focus of the lesson is on structure and function, as opposed to the less useful memorization of bones and their locations. As students also learn about the skeletal system, they also learn about various aspects of NOS. Here students have the particular opportunity to learn that scientific knowledge is tentative, scientific conclusions are a result of human creativity and subjectivity, scientific knowledge is derived from observations and inferences, and that scientific investigations can take a variety of forms as opposed to a single step-wise scientific method.

Grade Level: Middle and High School
Targeted NOS Aspects: tentativeness, subjectivity, creativity, observation, inference, empirically based
Discipline: Biology
Prerequisite knowledge: minimal knowledge of skeletal systems
Instructional Scenario:

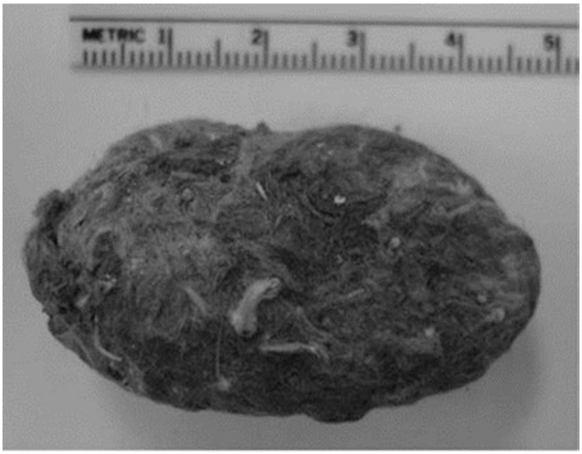
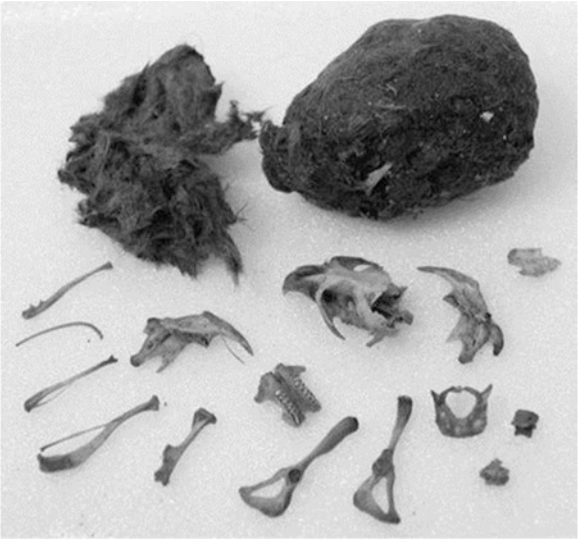


Fig. 17.14 A typical owl pellet as found (left)

Fig. 17.15 Common bones and other materials found in a typical owl pellet (right)



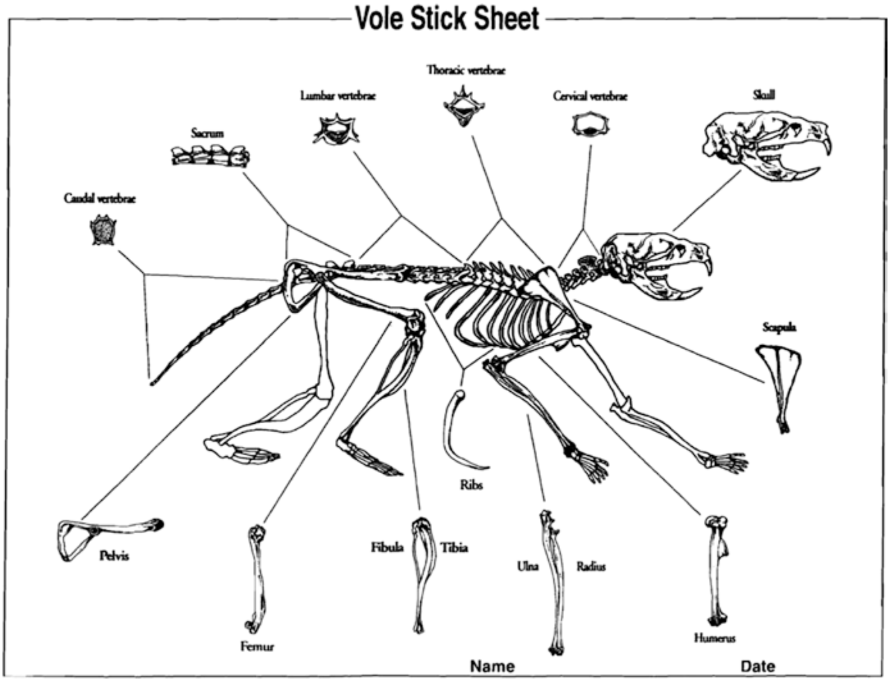


Fig. 17.16 Vole bones as an example of a typical animal found in an owl pellet

Fig. 17.17 Disarticulated skeleton (note that cat, rabbit, and mink skeletons are very similar)

1. On the first day that students begin their study of skeletal systems, give pairs of students an owl pellet (Figs. 17.14 and 17.15). Have them dissect the pellet to find the bones within the pellet. (Teacher background information: Owl pellets are indigestible food regurgitated by barn owls several times a day. Since bones are not digestible by the owls they are embedded within the pellets. These can be collected from barns or purchased from many biological or scientific supply companies).
2. After all the bones are removed from the pellets, ask students to match the bones on the vole diagram (Fig. 17.16) and tape the dissected bones in the appropriate position on the diagram.
3. Next, hold a class discussion about the structure/form of the various bones and their locations in the vole skeleton. Students are asked where the largest and thickest bones are found and where the smallest and thinnest bones are found. The goal of the discussion is to have students realize that the structure/form of the various bones is related to their function and location (e.g., supporting weight, protection, etc.).
4. Next, give students a disarticulated skeleton of an unidentified animal and, in groups of 4–5, have them assemble the skeleton. Students should use the background knowledge of skeletons that they learned from the owl pellet activity to infer the structure of this new and unidentified animal (Fig. 17.17). (Note: We have used disarticulated skeletons from rabbits, cats, and minks that have been purchased from a biological supply company or borrowed from a local university.)
5. Following this, engage students in another discussion about the structure and functions of the bones in the skeleton. The point of this discussion is to

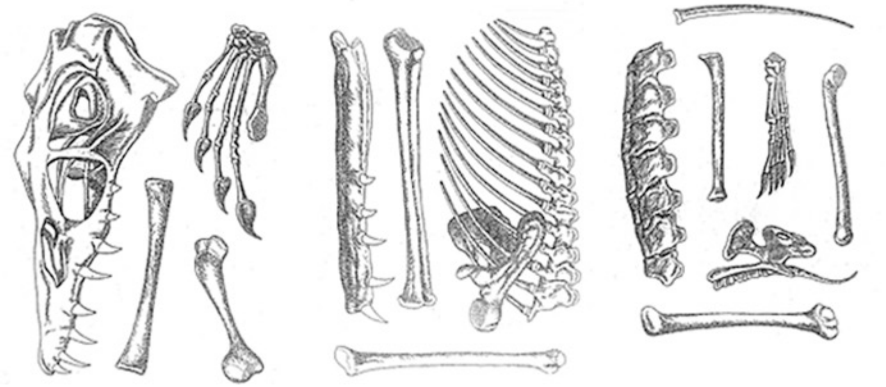


Fig. 17.18 Mystery bones

solidify the relationship between the structure and functions of bones in the skeletal system rather than to identify the animal from which the bones come. Ask students if what they have been doing is related to the work of scientists. That is, do some scientists spend their time piecing together fossilized bones? Ask students if this type of scientific investigation follows the "scientific method" as it is portrayed in their textbooks.

6. To equate the work of the students to that of scientists, give each student group an envelope containing the set of bones from an extinct animal which you have printed on laminated paper (Fig. 17.18). Have students use their knowledge of skeletal systems to construct the animal's skeletal system, just as paleobiologists do.
7. Students should be encouraged to circulate and view the constructions of other groups out of curiosity or to help them with their own constructions. As constructions near completion, the teacher should take pictures of the various constructions with available technology for later projection in the classroom.
8. The construction of each group is projected for class discussion. Each group explains the reasons for the placement of the bones in the constructed skeleton. As this is done, the teacher questions students about the process and the various aspects of NOS that are evident in students' construction of the skeletal (e.g., creativity, tentativeness, subjectivity, etc.).
9. The teacher should now reveal scientists' construction of the skeleton and the inferred appearance of the animal with its skin on (Figs. 17.19 and 17.20). Students are often surprised to see the placement of the bones extending from the forearm digit of the animal because they have previously only seen the skeletons of terrestrial animals.
10. The teacher explains that the organism for which they constructed the skeleton was believed to be one of the first dinosaurs or reptiles that could glide. In the discussion, emphasize its resemblance to a reptile, which constitutes

Fig. 17.19 Reconstructed skeleton of *Scaphognathus crassirostris* (left)

Fig. 17.20 One paleontologist's imaginative reconstruction of *Scaphognathus crassirostris* (right)

the lingering debates between the relationship between dinosaurs and reptiles (Teacher background information: This creature lived in Europe during the Late Jurassic period). From its first discovery in 1831 there has always

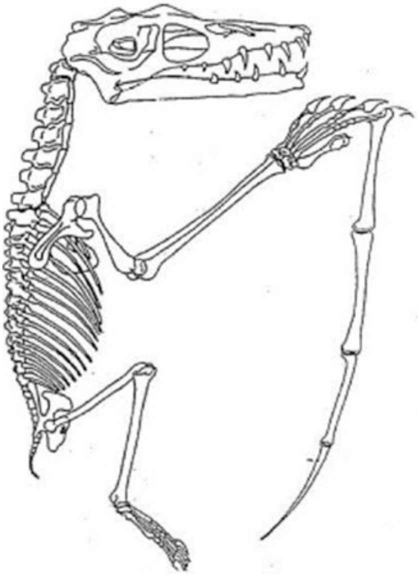


Fig. 17.21 Another reconstructed skeleton of *Scaphognathus crassirostris* (left)

Fig. 17.22 Another paleontologist's reconstruction of *Scaphognathus crassirostris* (right)

been some confusion concerning whether this creature was an early dinosaur or extinct reptile.

11. Inform students that recently, scientists have decided that the bones supporting the wing in Fig. 17.19 should be moved to the second forearm digit to

better support the wing. Ask students how this relates to NOS. They should identify that scientific knowledge is subject to change.

12. Now, show students Figs. 17.21 and 17.22 and ask them to compare the appearance of Fig.17.19 to Fig. 17.20.
13. The students quickly notice that Fig. 17.22 is more birdlike as opposed to resembling a reptile. The teacher explains that we now currently believe that dinosaurs are related to birds, and this has led to a different interpretation of what the animal looks like with skin. If it is a high school class that has studied, or are studying, evolution, the teacher could ask students why the inferred appearance has changed. In summary, this activity fits quite nicely in a biology class during the study of skeletal systems and the form and function of bones while simultaneously integrating aspects of the nature of science.

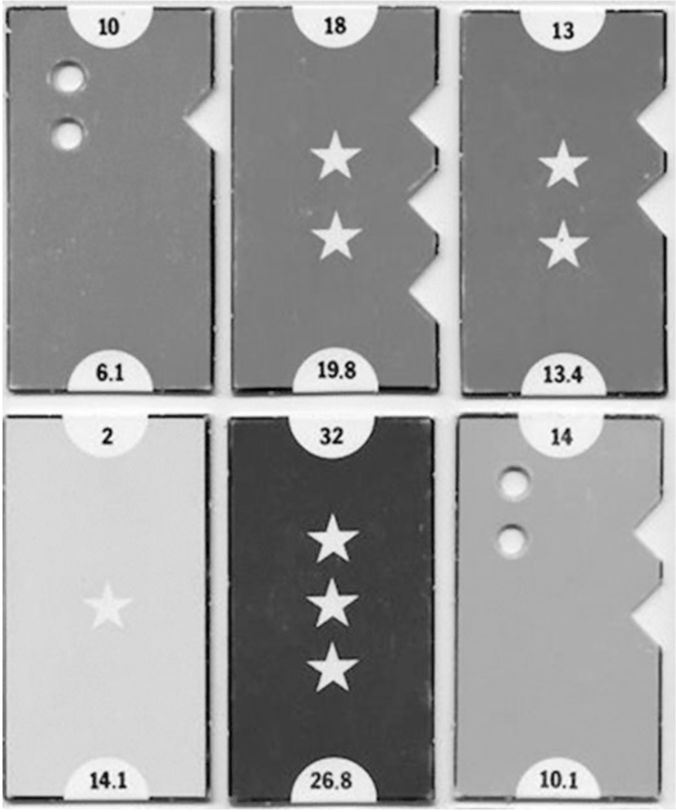


Fig. 17.23 Periodic table activity cards. (Available from American Educational Products)

17.2.7 The Periodic Table

The periodic table is presented in every chemistry and physical science class, and it is used repeatedly throughout the course. The table serves as an organizational scheme for the elements. Unfortunately, few students understand how the table was developed. The following activity is a concrete representation of how the periodic table was developed by Mendeleev in the 1860s.

Grade Level: Middle and High School
Targeted NOS Aspects: tentativeness, subjectivity, creativity observation, inference, empirically based
Discipline: Chemistry
Prerequisite knowledge: Minimal knowledge of elements and matter
Materials: Colored cards with figures and numbers can be purchased directly from the manufacturer *American Educational Products* (https://www.amep.com/) and perhaps through other online retailers.
Instructional Scenario:

1. Using the set of cards illustrated in Fig. 17.23, remove the light green card with the number 14 at the top from each set of cards. Without any introduction to the periodic table, give each student group a set of the remaining 23 cards.
2. Ask students to arrange the cards into some organizational scheme based on the properties they observe on the cards. Give them no more than 2 min for this task.
3. Have the students in their groups share results. Students' patterns might be organized by the numbers at the top and bottom, the color of the card, or the notches or shapes within the cards. Ask the students why different groups prioritized different attributes on the cards to organize them? This presents an opportunity to discuss subjectivity and creativity.
4. Next, the teacher informs the students that there is a missing card from the sets and asks the students to use their original organizational scheme or create a new one to determine what the missing card might look like. Give the students at least 20 min for this part of the activity.
5. Have a volunteer from each group draw their missing card on the board, making sure they include all the attributes that they infer are on the card. This will allow them to compare the groups' conclusions (inferences) are different. This can extend to a discussion of observation and inference in science.
6. Ask students if their organizational scheme changed when they were trying to describe the missing card. Many groups will say yes, and this is a good time to discuss that scientific knowledge is subject to change with the introduction of new data (i.e., there is a card missing). The discussion of students' organizational schemes and inferences about the missing card can also address other aspects of nature of science and scientific inquiry. For exam-

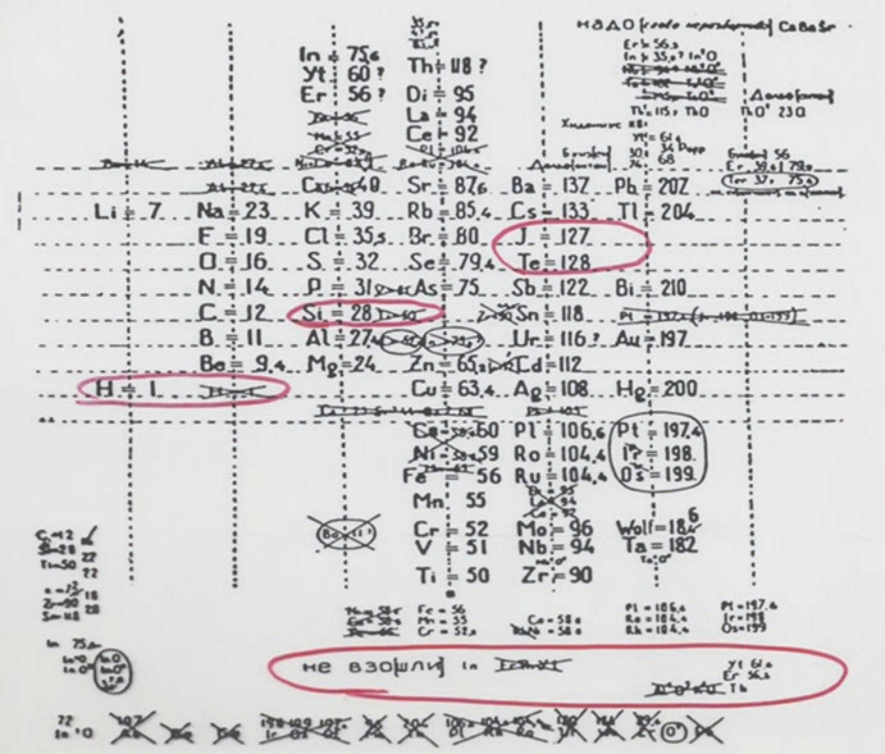


Fig. 17.24 English translation of Mendeleev's periodic table. (Hoffmann and Torrence 1993, p. 33)

ple, in arranging the cards, students may not consider all the properties (color, a decimal number, an integer, a set of side notches, a set of holes, and a set of stars) of the cards.

Some students may ignore some of the properties. In addition, even though the same properties of the cards were considered, the classification schemes of the cards may be different from each other. Ask your students "Why did you consider different properties?" "Can scientists develop different inferences from the same data?" Explain to students that scientists' investigations are conducted in the matrix of their background knowledge (theories). Scientists often reach different conclusions based on the same data, just as the students have done.

7. Ask students, "How can you resolve the different inferences about the missing card?" Explain to students that not all inferences in science are acceptable. Inferences should be based on and consistent with empirical data. At this point, the class can evaluate which inferences were more valid and consistent with the data.

8. At this point, the teacher can increase student interest by showing them the missing card or the teacher could choose not to show students the card if the goal is to emphasize that scientists cannot usually see the real answer in nature, but they must infer from the empirical evidence obtained through investigations.
9. It is important to let the students know that this activity mirrors what chemists such as Mendeleev did in developing the periodic table. It was not just a problem-solving activity using cards. At the time, there were numerous organizational schemes for the chemical elements proposed throughout the late nineteenth century. Mendeleev himself proposed several. In the end, the unique vision of Mendeleev was that he organized the elements based on their atomic weights.
10. Mendeleev wrote out his plan in his native language of Russian but there is an English translation (Fig. 17.24). Mention to students that the chart is rotated 90 degrees to the left of how we presently represent the table. Be sure to direct their attention to the portions of the table that are circled.
11. Ask students to look carefully at the table and see if they notice anything interesting or, to be time efficient, point out certain intriguing observations. For example, have students note that titanium (Ti), next to silicon (Si), is crossed out and hydrogen's (H) position has been moved. At the bottom of the table is a tally of elements to be placed into the table. Above the tally, in abbreviated Russian, it says "Don't Fit: In, Ee, Th, Y." Finally, the atomic weight of tellurium (Te) was thought to be greater than iodine (I), but tellurium is placed before iodine in the table. For some reason, Mendeleev felt that the estimated weights were slightly incorrect. The table also had gaps in it. Mendeleev felt that there are elements yet to be discovered, much like the missing card in the activity.
12. After noting the above observations about the table, the class should discuss the role of creativity in science and that the table was really a creation by Mendeleev, with ongoing changes being made as new elements were discovered.
13. If you have a class of preservice or inservice teachers, they might be interested to know that Mendeleev had been asked to teach a chemistry class at a local university and the periodic table was his way of organizing everything he knew about the elements. In effect, the periodic table was his instructional plan or course syllabus.

17.3 Summary

We believe that these activities illustrate how aspects of NOS can easily be integrated into existing science curriculum. It is important to note that the activities are not stand-alone activities to teach NOS. Rather, each includes a suggested science content context into which these activities can be included to facilitate students' understandings of subject matter as well as NOS. Teachers should not feel a need to create totally new instructional activities to integrate NOS into the curriculum. Most science activities can be modified to stress one or more aspects of NOS in addition to the traditional science content intended. With some careful planning the related NOS aspects will rise to the surface.

References

American Association for the Advancement of Science (AAAS). (1993). *Benchmarks for science literacy*. New York: Oxford University Press, Inc.

Bell, R., Blair, L., Lederman, N. G., & Crawford, B. (2003). Just do it? Impact of a science apprenticeship on high school students' understandings of the nature of science and scientific inquiry. *Journal of Research in Science Teaching, 40*(5), 487–509.

Hoffmann, R., & Torrence, V. (1993). *Chemistry imagined: Reflections on science*. Washington, DC: Smithsonian Institute Press.

Hrdy, S. B. (1986). Empathy, polyandry, and the myth of the coy female. In R. Bleier (Ed.), *Feminist approaches to science* (pp. 119–146). New York: Pergamon Publishers.

Kuhn, T. (1970). *The structure of scientific revolutions* (2nd ed.). Chicago: The University of Press.

Lederman, N. G. (2007). Nature of science: Past, present, and future. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 831–879). Mahwah: Lawrence Erlbaum.

Lederman, N. G., & Abd-El-Khalick, F. (1998). Avoiding de-natured science: Activities that promote understandings of the nature of science. In W. F. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 83–126). Dordrecht: Kluwer Academic Publishers.

Lederman, N. G., & Lederman, J. S. (2014). Research on teaching and learning of nature of science. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of research on science education* (Vol. II, pp. 600–620). New York: Routledge.

Lovejoy, C. O. (1981). The origin of man. *Science, 211*, 341–350.

National Research Council (NRC). (1996). *National science education standards*. Washington, DC: National Academies Press.

National Science Teachers Association (NSTA). (1982). *Science-technology-society: Science education for the 1980*. Washington, DC: Author.

NGSS Lead States. (2013). *Next generation science standards: For states, by states*. Washington, DC: National Academies Press.

Chapter 18
Blending Nature of Science with Science Content Learning

Irene Neumann, Hanno Michel, and Nikos Papadouris

18.1 Introduction

Several approaches to teaching aspects of NOS have been suggested so far, e.g., through historical case studies (e.g., Irwin 2000), in inquiry settings (e.g., Khishfe and Abd-El-Khalick 2002; Schwartz et al. 2004), or by means of generic activities (as discussed by Lederman, Abd-El-Khalick, and Lederman in Chap. 17. Despite these advancements in our knowledge, as a research community, about NOS teaching and learning, it is the case that teachers still seem to have difficulties including NOS in their actual instructional practice. Some of them might regard an implicit teaching of NOS as sufficient (which several studies contradict; see, e.g., Khishfe and Abd-El-Khalick 2002), or they see NOS teaching as an optional component for which there is no time in class (Clough 2006). However, science instruction always conveys views about NOS, and if these views are not exposed to explicit teaching elaboration, students are liable to develop (or reinforce) epistemologically flawed ideas which might act as barriers to future learning (Clough 2006). At the same time, scientific concepts inherently carry content-specific NOS aspects (Bächtold and Guedj 2014; Brigandt 2010; Papadouris and Constantinou 2017), which could be easily elaborated together with canonical disciplinary aspects without devoting much additional time. Blending science content and NOS aspects in a way that they mutually support each other could

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_18

promote integrated learning experiences. In this chapter, we will discuss some general strategies to design blended NOS and science content instruction, and provide details on four respective activities in the context of energy. In doing so, we argue for explicitly engaging students in discussions about epistemic and ontological aspects of science concepts (e.g., notions about the status and the value of such concepts), which can be used to illustrate important aspects of NOS, while at the same time allowing students to build canonical conceptual understanding.

18.2 Blending NOS and Science Content Instruction

School science education typically addresses content knowledge, such as knowledge about energy, acids and bases, or genes. Such scientific concepts entail several characteristics, aspects, and relationships, which constitute the body of the science disciplinary knowledge. However, there also is a meta-level to this knowledge, comprised of epistemic and ontological aspects related to each concept (e.g., Bächtold and Guedj 2014; Brigandt 2010). It is important to help students understand and appreciate these aspects (e.g., the status and utility of the various) and at the same time provide a link to aspects of NOS in general (Duschl 1990; Driver et al. 1996; Erduran et al. 2007). Blending NOS and science content instruction is one way to address this meta-level in science education. By blending, we mean to refer to the explicit coupling of scientific content with discussions about NOS aspects ("epistemic discourse"; see Papadouris and Constantinou 2014). As such, blending NOS with content knowledge usually involves coordinating among three components: (1) general ideas about NOS, that is, "the epistemology and sociology of science, science as a way of knowing, or the values and beliefs inherent to scientific knowledge and its development" (Lederman et al. 2002, p. 498); (2) the canonical content knowledge per se, that is, the scientific concepts; and (3) NOS ideas directly connected to (and exemplified by) the respective content,[1] that is, epistemic and ontological aspects of scientific concepts. In the following, we suggest three approaches to interweaving these components in the classroom.

The first approach involves starting from disciplinary content knowledge and subsequently shifting the focus to relevant general or *content-specific NOS* ideas. For developing students' content knowledge, often hands-on activities such as doing scientific inquiry are used. After elaborating the conceptual aspect of these activities, students might be engaged in reflection on what they actually did in these

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[1] Papadouris and Constantinou (2017) argue for integrating epistemic and ontological aspects of scientific concepts in science teaching to promote students' NOS understanding. In this chapter, we will refer to such aspects as "content-specific NOS ideas" to illustrate their connection to NOS and their value in promoting both conceptual and NOS understanding.

activities (e.g., through classroom discussions or lab journals; e.g., Schwartz et al. 2004) and use this as a context to highlight general and content-specific NOS aspects. For example, by relating their own approaches to the work of scientists, students may become aware of the fact that science is evidence-based, that it shares methods but does not always follow a stepwise plan, or that creativity is a vital feature of scientific inquiry. Such reflection may also illustrate epistemic and ontological features of the scientific concepts investigated in the activities, such as the theoretical and invented nature of the respective scientific concept, or it may address the utility of these concepts for explaining a broad range of phenomena or allowing for predictions. This would help students to understand and appreciate the epistemic value of the various concepts in science in terms of the added value that they bring in the interpretive and predictive capability of science. In addition, this might also raise students' interest towards science and science teaching/learning.

The second approach involves starting with content-specific NOS ideas and then making connections to general NOS ideas and/or the canonical aspects of scientific concepts. Papadouris and Constantinou provide a list of selection criteria for epistemic and ontological aspects that are suitable for inclusion in science education: such aspects should be "(a) simple enough to lend themselves to teaching elaboration in school science, (b) sufficiently uncontroversial, so that disagreements among philosophers of science can remain reasonably unexplored, and (c) likely to serve a productive role in the students' learning trajectories" (Papadouris and Constantinou 2017, p. 665). Addressing content-specific NOS ideas of a scientific concept may be promoted, for example, by engaging students in the process of reviewing texts by scientists or philosophers (Richard Feynman, for instance, repeatedly elaborates on such aspects in his famous lectures) and reflecting on associated epistemological considerations. Another approach would be to exemplify, for example, the cross-cutting nature and explanatory power of a specific concept by illustrating its application to a broad variety of different phenomena. When students have become aware of the content-specific NOS aspects, teachers could guide them to generalize these aspects to other scientific concepts and thus successively discuss the features of scientific knowledge in general (that is addressing general NOS aspects); likewise, teachers may use the content-specific NOS aspects as a starting point to elaborate on further canonical content aspects. Accordingly, this approach is most suitable for addressing NOS aspects that directly relate to scientific knowledge as the product of science, such as definitions of laws and theories, or the human-conceived and subjective nature of scientific knowledge.

Finally, the third approach involves starting from general NOS ideas and then making connections to canonical content aspects or to content-specific NOS aspects. Historical narratives about scientific inquiry or disputes within the scientific community can be used to emphasize NOS aspects such as the social and cultural influences on science or the important role of creativity in science. At the same time, they depict scientific knowledge as a human product. Such narratives may also be used to discuss what these general NOS features mean with respect to specific scientific concepts, or they may serve to facilitate the development of deeper insights into these concepts themselves. Alternatively, narratives from current frontier research (such as current debates about dark energy or dark matter) may serve as examples that scientific knowledge is still evolving and is tentative in nature. Subsequently, quality criteria for scientific theories could be introduced and be connected to specific scientific concepts and theories in particular, illustrating their human-conceived nature, as well as their utility and value in science. This can be used as a starting point to explore disciplinary content aspects of these science concepts and consecutively build up a sound understanding among students.

In the next part, we will illustrate how blended NOS and science content instruction can be realized for a specific scientific concept: energy. We will identify the main disciplinary and content-related NOS aspects, as well as general NOS aspects that can be discussed in the context of energy, and will present four respective activities. The activity "Energy – One concept, many forms" provides an example for the first approach described above. The activity "Feynman's description of energy and energy conservation" illustrates the second approach. Finally, the activities "Mayer and Joule – Pathfinders to the law of energy conservation" and "Dark Energy – A frontier question of science" exemplify the two alternatives for realizing the third approach, as described above. In addition to illustrating the above three approaches in context, the four activities are also meant to convey a sense of the variation as to how the three approaches may play out in the classroom environment.

18.3 Designing Blended Instruction in the Context of Energy

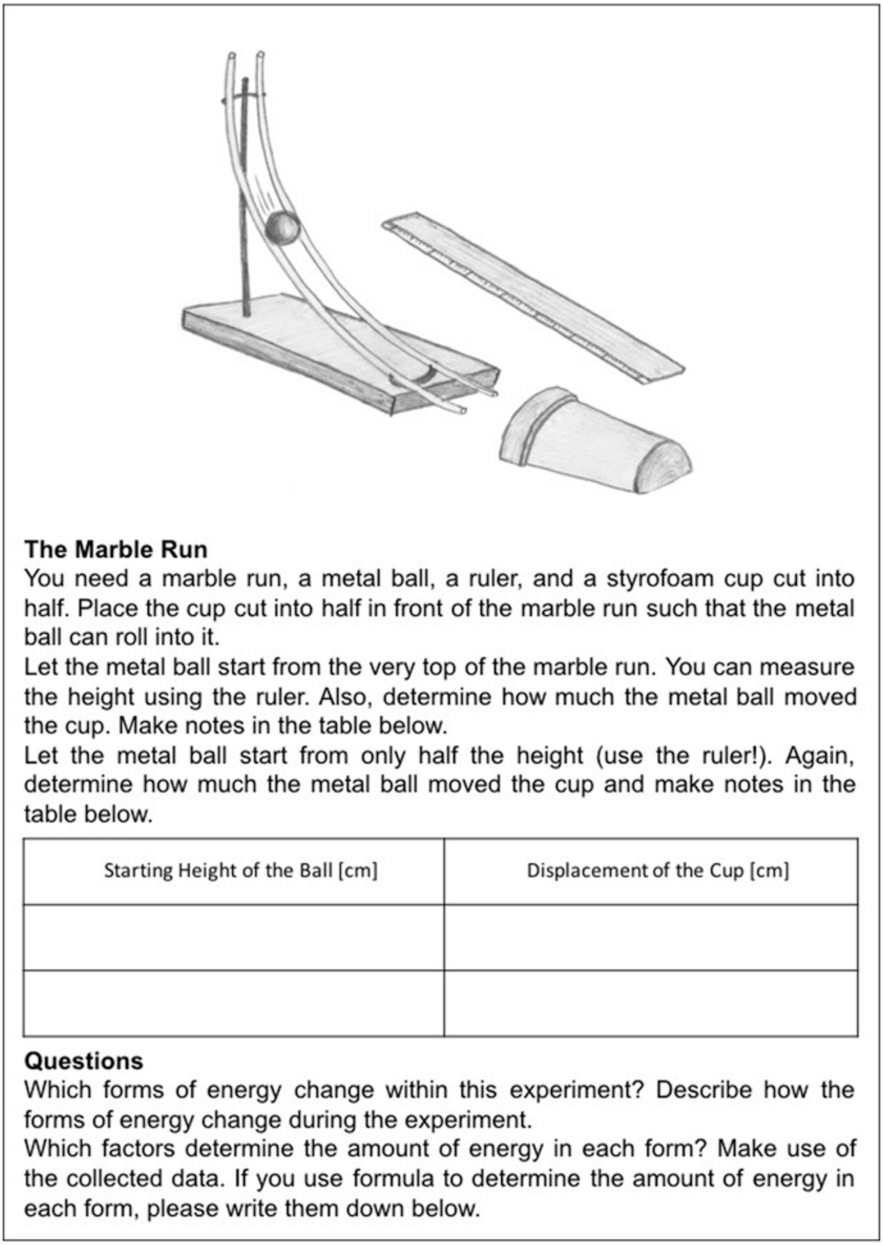
Energy is a core concept of science, and of physics in particular (e.g., Duit and Neumann 2014; Neumann et al. 2013). In the literature, there seems to be a consensus about the importance of teaching four (sometimes five) aspects of energy: energy forms, transfer, transformation, and conservation (and degradation) (Neumann et al. 2013), which are typically addressed in science instruction in an explicit manner. In addition to these canonical aspects of energy, students could be also guided – probably mostly implicitly – to appreciate energy as a human-conceived construct, an abstract, mathematical concept (rather than a concrete physical object or some material that one could directly manipulate) which holds high explanatory and predictive power as it helps to explain and unify various phenomena and to predict scientific processes (by excluding system states that contradict energy conservation) (Papadouris and Constantinou 2017). We label these aspects – the invented and mathematical nature, the exploratory and predictive power, and the unifying, cross-cutting nature of energy – as *content-specific NOS ideas* connected to energy. Addressing these aspects can be meaningfully connected to discussing NOS aspects of scientific knowledge in general. For example, teaching about the explanatory and predictive power of energy can be connected with teaching about the value of scientific theories in general. Likewise, discussing the invented nature of energy may serve as a means to teach about creativity in scientific inquiry. On the other hand, appreciating the content-specific NOS ideas of energy together with the canonical aspects may help students to engage in the process of employing energy as a framework for analyzing physical systems, in a more meaningful and coherent manner (Papadouris and Constantinou 2014). Also, one may argue that developing coherent understanding of energy requires appreciating both the canonical aspects and content-specific NOS ideas.

18.4 Activity 1: "Energy – One Concept, Many Forms"

Targeted NOS aspects: scientific knowledge requires evidence; cross-cutting nature of energy (energy-specific).

This activity starts with two hands-on experiments addressing different forms of energy (Figs. 18.1 and 18.2). In the first experiment, "The marble run," students are asked to let a metal ball roll down a marble run, starting from different heights. The ball rolls into a styrofoam cup, which thus is pushed away. The students are then asked to make notes how much the cup has been moved depending on the ball's starting height. This experiment is meant to introduce two forms of energy, kinetic and gravitational potential, and illustrate factors determining changes in the amount of kinetic and gravitational potential energy. The second experiment, "The balloons," addresses another form of energy, that is, thermal energy. Students are asked to heat two balloons, one including a small amount of water, until they burst. Students are engaged in an energy analysis of these two cases. Again, students are asked to identify the factors determining the balloons' thermal energy. After the students conduct these two experiments, they engage with reflective discussions on both content-specific and general NOS aspects.

18.4.1 Hands-On Experiments



The Marble Run

You need a marble run, a metal ball, a ruler, and a styrofoam cup cut into half. Place the cup cut into half in front of the marble run such that the metal ball can roll into it.

Let the metal ball start from the very top of the marble run. You can measure the height using the ruler. Also, determine how much the metal ball moved the cup. Make notes in the table below.

Let the metal ball start from only half the height (use the ruler!). Again, determine how much the metal ball moved the cup and make notes in the table below.

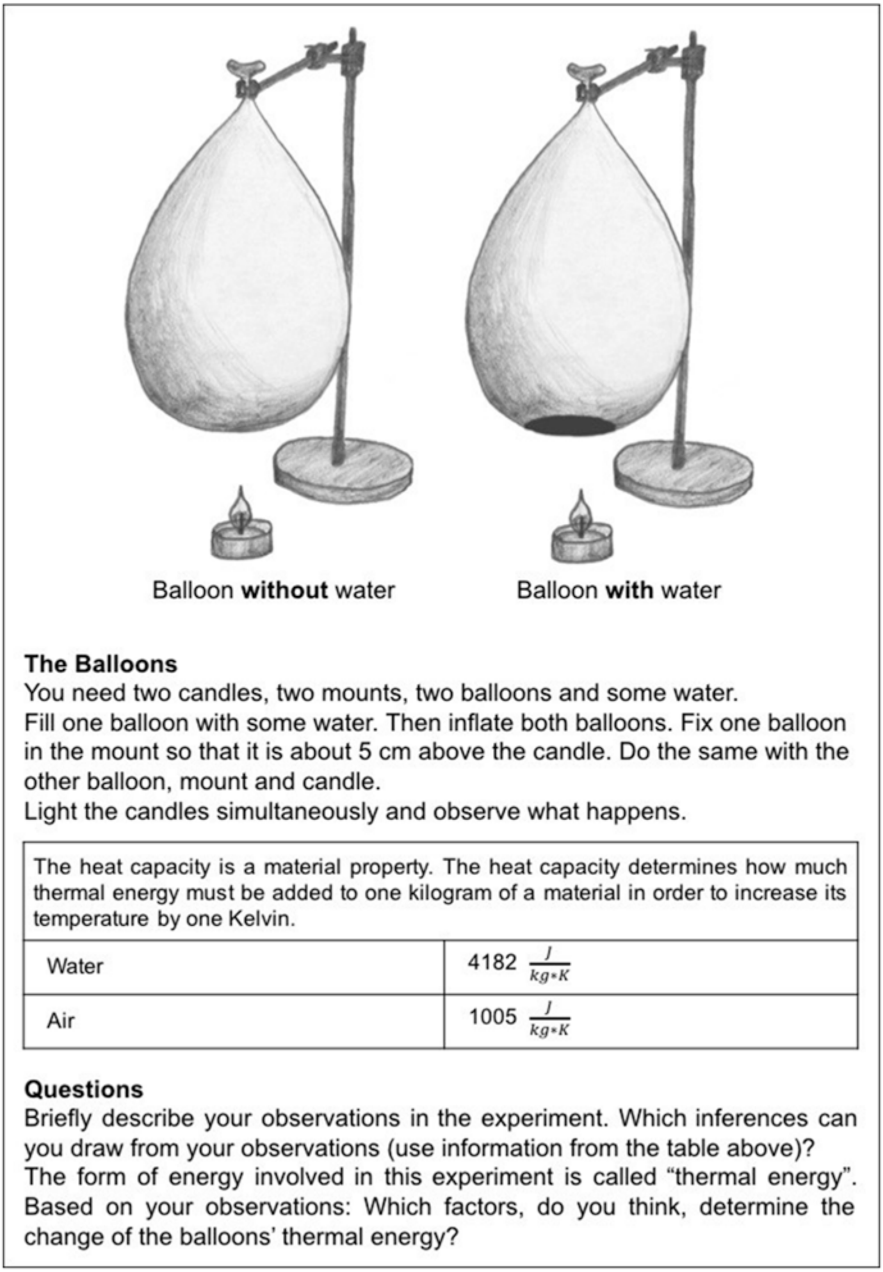
Starting Height of the Ball [cm]	Displacement of the Cup [cm]

Questions

Which forms of energy change within this experiment? Describe how the forms of energy change during the experiment.

Which factors determine the amount of energy in each form? Make use of the collected data. If you use formula to determine the amount of energy in each form, please write them down below.

Fig. 18.1 Instructions for hands-on experiment 1: "The marble run"



Balloon **without** water

Balloon **with** water

The Balloons

You need two candles, two mounts, two balloons and some water.

Fill one balloon with some water. Then inflate both balloons. Fix one balloon in the mount so that it is about 5 cm above the candle. Do the same with the other balloon, mount and candle.

Light the candles simultaneously and observe what happens.

The heat capacity is a material property. The heat capacity determines how much thermal energy must be added to one kilogram of a material in order to increase its temperature by one Kelvin.	
Water	$4182 \frac{J}{kg*K}$
Air	$1005 \frac{J}{kg*K}$

Questions

Briefly describe your observations in the experiment. Which inferences can you draw from your observations (use information from the table above)?

The form of energy involved in this experiment is called "thermal energy". Based on your observations: Which factors, do you think, determine the change of the balloons' thermal energy?

Fig. 18.2 Instructions for hands-on experiment 2: "The balloons" (adapted from https://www.forschungs-werkstatt.de/wp-content/uploads/2014/12/Luftballon_ueber_Kerze.pdf)

18.4.2 Reflective Discussion

The following questions can guide a discussion connecting the canonical aspects of energy with the relevant energy-specific, as well the more general, NOS aspects. Of course, reflecting on experiments and hands-on activities can be used to address other NOS aspects as well; the guiding questions here only serve as examples. Further questions could, for example, address the difference between observations and inference or the multiple ways of scientific inquiry. The following questions help to illustrate the fact that scientific knowledge requires evidence and the cross-cutting nature of energy:

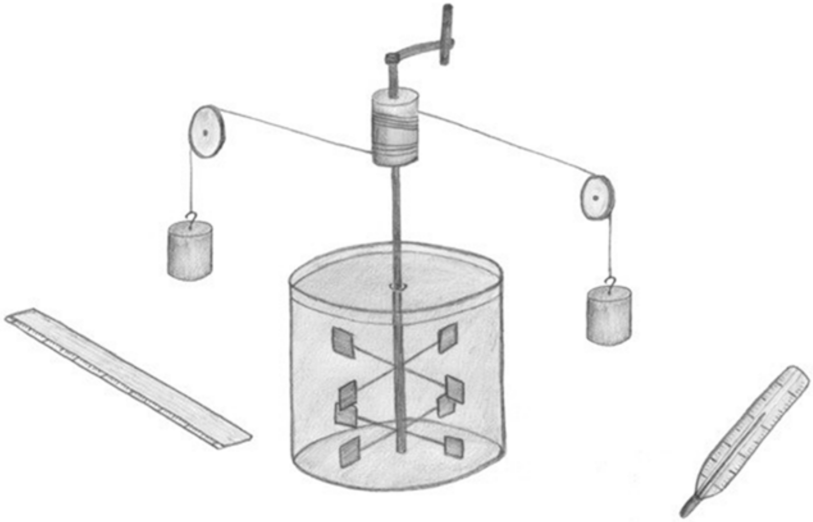
- Do scientists have to conduct experiments (like the ones you conducted) to develop scientific knowledge?
  Often, scientific knowledge does not just follow from theoretical considerations and cannot generally be proven to be true, but it requires evidence to support it. Experiments provide one approach towards corroborating scientific claims but there can be others.
- Different forms of energy are described by different mathematical formulae (e.g., gravitational, kinetic, or thermal energy). Why do scientists use the same word "energy" for these different entities?
  While there are different formulae for the different forms of energy, they can be transformed into each other, with the total amount of energy staying the same. Changes in the amount of energy stored in different forms have to be calculated taking into account the relevant energy transfers and cannot be measured directly. The concept of energy helps scientists interrelate different phenomena and allows for a unified approach towards analyzing physical systems.

18.5 Activity 2: "Mayer and Joule – Pathfinders to the Law of Energy Conservation"

Addressed NOS aspects: scientific knowledge is tentative, durable, and self-correcting; subjectivity; social and cultural influences.

This activity links a hands-on experiment with a historical case. In particular, students enact a hands-on activity that resembles the experiment originally conducted by Joule to determine the mechanical equivalent of heat (Fig. 18.3). In addition, students are provided with some historical background notes about the establishment of the mechanical equivalent of heat. In the experiment, students experience how mechanical energy is transformed into thermal energy, which is illustrated by a rise in temperature of the water inside the bowl. Thus, the activity introduces the important aspects of energy transformation and conservation to students, while the narrative at the same time allows discussing various aspects of NOS.

18.5.1 Hands-On Experiment



Experiment (so-called Joule's Experiment)

You need a bowl of water, an apparatus as shown in the picture ('Joule's experiment'), cord, two weights, a thermometer, a scale and a calculator. Determine the weight of the weights, as well as of the water in the bowl. Put the apparatus in the bowl and fix the weights to the cord as shown in the picture. Use the thermometer to measure the temperature of the water. Now wind up the cord and measure the height of the weights above the ground. Now release the cord so that the weights fall down. Measure the temperature of the water again.

Entity	Measurement (with unit)
Masses of the weights	
Mass of the water	
Starting height of the weights	
Temperature of the water before the fall	
Temperature of the water after the fall	

Calculate the potential energy of the weights before and after the fall:
$\boldsymbol{E_{pot} = m * g * h}$ with m = mass of the weights, h = height (before/after), g = gravitational acceleration (9,81 m/s²); and determine the change in potential energy due to the fall.
Calculate the change of thermal energy of the cylinder: $\boldsymbol{\Delta E_{heat} = m * c_m * \Delta T_m}$ with m = mass of the water, ΔT_m = difference in temperature before/after the fall, c_m = specific heat capacity of water (ca. $4182 \frac{J}{kg*K}$).
Compare your results! What do you notice?

Fig. 18.3 Instructions for Joule's experiment

18.5.2 Historical Background: A Reading for Students

Mayer and Joule: Discovering the Conservation of Energy.

The insight that thermal phenomena and energy are related is traced back to two scientists, the German Julius Robert Mayer (1814–1878) and the British James Prescott Joule (1818–1889). Mayer was a ship's doctor who traveled the world. On his journeys, he observed that the color of human's blood is different in warmer regions than in colder regions. He already knew that the color of blood is related to chemical processes in a human's body. Therefore, he thought that in warmer regions, some energy necessary for these chemical processes is provided by the heat from the surrounding. That is, he assumed a relationship between energy and changes in temperature. Mayer then wanted to publish his findings in a well-respected journal. However, the journal editors rejected his paper, probably because he was a mostly unknown medical doctor without much reputation in the scientific community.

At about the same time, Joule was also exploring the relationship between energy and temperature changes. He developed a mechanism which coupled a liquid with a falling stone. He then investigated how much the temperature of the liquid increases due to the stone falling. That is, he investigated the relationship between changes in thermal energy and potential energy. Joule further and further refined his apparatus and quantified this relationship very precisely. His experiments were published in an article "On the Existence of an Equivalent Relation Between Heat and the Ordinary Forms of Mechanical Power." This shows that Joule (such as Mayer) obviously realized the equivalence between thermal and mechanical energy as just two forms of the same entity.

Any real process involves the transformation of (at least some) energy to thermal energy (dispersed in the surrounding air). Unless one is able to appreciate the connection between temperature increase and energy, this dissipated amount of energy seems to be lost, thereby refuting energy conservation. The law of energy conservation, which plays a crucial role in science, could thus only be formulated based on the relation between thermal and mechanical energy. Indeed, Joule's and Mayer's work had paved the way towards the development of generalized energy conservation law that extends beyond idealized, nonfrictional mechanical systems.

18.5.3 Reflective Discussion

The above text can be used as a starting point to discuss NOS aspects, such as the tentative nature of scientific knowledge. However, students may experience difficulties in acknowledging such aspects. If students do not bring up this notion themselves, the teacher should point them out, e.g., by initiating a discussion about general and energy-specific NOS-aspects:

- Why was it difficult for scientists to formulate the generalized law of energy conservation right away?

Until thermal energy was regarded as a form of energy, the law of energy conservation could not have been postulated, as in every non-idealized process, some amount of energy is dissipated through heat, and thus would otherwise be regarded as being "lost." The work of Mayer and Joule is thus an example for the tentative and evolving nature of scientific knowledge.

- Why do you think the scientific community did not pay attention to Robert Mayer's work on energy conservation in the first place?
  The acceptance of new concepts and theories can be inhibited, regardless of whether they might later turn out to be useful. New theories are only accepted if they are properly supported by evidence.
  The acceptance of new ideas also depends on the compatibility between these ideas and the currently established consensus (or paradigm) within the scientific community as well as the position and reputation of the people who introduce them, adding a social element to scientific inquiry.

18.6 Activity 3: "Feynman's Description of Energy Forms and Conservation"

Targeted NOS aspects: scientific knowledge requires evidence; difference between observation and inference; creativity; science has limits (general NOS); human-conceived and cross-cutting nature of energy, explanatory power of energy (energy-specific).

The well-known physicist and Nobel Laureate Richard Feynman vividly described how difficult it is to define energy and why energy conservation is such a powerful concept (Feynman, Leighton, & Sands 1963). This piece of the so-called Feynman lectures may be used as a starting point for a discussion about energy-specific, as well as general NOS aspects. The activity is designed as a reading assignment. Given the length of the original Feynman lecture, we will only summarize it here. The full text is available at http://www.feynmanlectures.caltech.edu/I_04.html.

18.6.1 Students' Reading Assignment

Feynman starts with a metaphor to explain the conservation of energy, introducing a boy, Dennis, who owns an exact number of building blocks. Every day, Dennis' mother collects and counts the building blocks. While sometimes there are more blocks than expected, sometimes there are fewer. In all these situations, Dennis' mother searches for a reason why it is not the expected number of blocks, successively developing a formula to determine the number of blocks that Dennis has hidden or that were brought in by a friend. "As a result, she finds a complex formula, a quantity which *has to be computed*, which always stays the same in her situation" (Feynman et al. 1963, 4–2). Feynman continues to introduce various forms of energy, while pointing out the mathematical and abstract nature of the energy concept. The piece ends with a description of conservation laws in physics, among them the conservation of energy, and Feynman notes: "If we had all the formulas for all kinds of energy, we could analyse how many processes should work without having to go into the details" (p. 4–7).

18.6.2 Epistemic Discourse

Feynman's lecture on energy serves as a context within which several aspects of NOS could be addressed through guiding questions such as the following:

- According to Feynman, what is energy? Why are the concept of energy and the law of conservation of energy so useful in science?
  Energy is not something to see, feel, or smell, but rather is a theoretical, human-conceived entity (as all scientific theories are human-conceived). Energy helps to explain various phenomena and serves as a cross-cutting, unifying concept. Furthermore, energy allows to predict the development of physical systems and phenomena as it helps to rule out system configurations not conserving energy.
- How did Dennis' mother come up with a formula for the number of blocks? To what extent is her approach similar to the work of scientists?
  There is a difference between observations (which represent relatively objective statements about natural phenomena) and inferences (which are human-conceived interpretations to explain these observations). Thus, the development of scientific knowledge involves creativity. Applying the law of energy conservation is an approach typical for theoretical physics and illustrates that there is no stepwise plan to do science but rather various approaches.

Teachers may use the whole lecture of Feynman's on energy (lecture 4) as a stand-alone unit, or use only parts of it, which could then be connected to students' learning of the different aspects of energy. For introducing the concept of energy, the first part with the metaphor of the building blocks can be used to make students sensitive towards the mathematical nature of the concept. This aspect can be introduced at an early stage in upper elementary school.

For a deeper discussion on the other energy-specific NOS aspects, and how these relate to other scientific concepts as well, it seems highly feasible that students are familiar with different forms of energy, as well as with the law of energy conservation and how it can be applied to describe and explain scientific phenomena, thus making it more adequate for students of the higher grades 10–12.

18.7 Activity 4: "Dark Energy – A Frontier Question of Science"

Targeted NOS aspects: there is no stepwise plan in scientific inquiry; subjectivity; social and cultural influences on science; science is tentative, durable, and self-correcting.

Historical cases are typically used to address the tentative nature of scientific knowledge. Discussing a topic from the current frontier of science (such as dark energy) may help students understand that until further theoretical or empirical evidence leads towards a certain direction, several theoretical approaches or possible explanations can persist parallel to each other. Students read a text that introduces dark energy (adapted from Hakim 2007; Lincoln and Nord 2014) and are then asked to design posters on dark energy which are used to guide an explicit discussion about NOS.

18.7.1 Students' Reading Assignment: The Expanding Universe

*In 1929, the American astronomer Edwin Hubble (1889–1953) recognized that nearly all stars and galaxies move away from us and from each other. This was a remarkable observation: At that time, it was already clear that stars and galaxies move, but scientists believed that the universe was overall static, that it neither expands nor collapses. Hubble's observations, however, would mean that the universe is expanding. Many scientists have since observed other distant objects, especially supernovae (*i.e., *exploding stars). From the observed brightness, they could identify the distance of the supernova from the earth, and using the speed of light they could calculate when the supernova happened. So, when comparing the velocity of nearer with that of more distant supernovae, scientists can infer how the expansion rate of the universe has changed. Most of the scientists strongly believed that the expansion of the universe would slow down due to gravitation. The observations, however, led to the exact opposite conclusion.*

There seems to be a force that drives the universe apart. Because there is currently no clear understanding about the origin of this force, scientists have labeled it "dark energy." What this dark energy is and how it can be described and explained is still under discussion among the scientists. One approach, for example, could be to extend Einstein's theory of general relativity by adding a so-called cosmological constant. Another approach postulates a dynamic energy field, the so-called quintessence. Both approaches provide a possible explanation for dark energy. This is an open issue that is currently being debated within the scientific community and *there is not yet consensus as to how to best account for the available empirical evidence.*

18.7.2 Reflective Discussion

Addressing issues from the current frontier of science is valuable from a NOS-perspective. However, it typically requires an understanding of rather complex scientific content. This activity is therefore not meant to have students develop a sound understanding of dark energy and the respective explanatory theories. Rather, the text is intended to provide students with basic information that could form a conceptual backdrop against which to discuss the respective NOS aspects.

Students could be asked to design a poster highlighting disciplinary aspects (e.g., the empirical findings that led to the postulation of dark energy, or approaches to explain dark energy), and NOS aspects based on the following guiding questions. The resulting representation of NOS aspects on the posters should then be explicitly discussed. In order to work on the poster, students may use additional resources (e.g., Hakim 2007; Harvey 2009; Lincoln and Nord 2014). Given the complexity of the topic, this activity should be applied in the higher grades 10–12.

- Why is it reasonable for scientists to assume that dark energy exists, even though they cannot directly observe it and they do not fully understand it?
  Theories and explanations can be deduced from empirical evidence but can also follow from theoretical considerations. In the case of dark energy, empirical evidence led scientists to raise the question for an explanation. Dark energy serves as such an explanation and was deduced from theoretical considerations.
- Why are there different ideas linked to the nature of dark energy, even if the scientists all draw on the same observations?
  Development in science involves interpretations of observations. These require creative thinking and are influenced by subjective and social/cultural factors.
- With the example of dark energy, how would you argue that scientific knowledge is tentative?
  Hubble's observations changed the way scientists understand the universe (static vs. *expanding), which illustrates that scientific knowledge is subject to change. Also, the concept of dark energy illustrates the tentative nature of scientific knowledge: Dark energy is a theoretical idea surround by substantial controversy within the scientific community. There needs to be more empirical evidence underpinning dark energy, and theories are needed, which explain dark energy and which at the same time are consistent with what is already known.*

18.8 Summary

In this chapter, we have sought to illustrate how NOS instruction can be intertwined with science content instruction. Far too often, teaching of NOS and of science content (at best) takes place parallel to each other with only few explicit connections. The activities described above reveal possible ways of enhancing useful links with NOS aspects. The selection to focus on energy is not intended to imply that the argument we have sought to develop relates to this content in a different way than any other science content. Indeed, it would have been possible to draw on many other examples, such as fields, force, atoms, evolution, or acids/bases. As such, we hope to enable readers (of various domains of science expertise) to gain insights into how the various approaches to blending NOS with content knowledge may play out in the science learning environment. This, in turn, could allow for generalizing and applying these approaches to other content of the science curriculum.

References

Bächtold, M., & Guedj, M. (2014). Teaching energy informed by the history and epistemology of the concept with implications for teacher education. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 211–243). Dordrecht: Springer.

Brigandt, I. (2010). The epistemic goal of a concept: Accounting for the rationality of semantic change and variation. *Synthese, 177*, 19–40.

Clough, M. P. (2006). Learners' responses to the demands of conceptual change: Considerations for effective nature of science instruction. *Science Education, 15*, 463–494.

Driver, R., Leach, J., Millar, R., & Scott, P. (1996). *Young people's images of science*. Buckingham: Open University Press.

Duit, R., & Neumann, K. (2014). Ideas for a teaching sequence for the concept of energy. *School Science Review, 96*(354), 63–66.

Duschl, R. A. (1990). *Restructuring science education: The importance of theories and their development*. New York: Teachers College Press.

Erduran, S., Bravo, A. A., & Mamlok-Naaman, R. (2007). Developing epistemologically empowered teachers: Examining the role of philosophy of chemistry in teacher education. *Science & Education, 16*(9–10), 975–989.

Feynman, R. P., Leighton, R. B., & Sands, M. L. (1963). *The Feynman lectures on physics*. Reading: Addison-Wesley.

Hakim, J. (2007). *Story of science: Einstein adds a new dimension. Story of science series*. Washington, DC: Smithsonian Books.

Harvey, A. (2009). Dark energy and the cosmological constant: A brief introduction. *European Journal of Physics, 30*(4), 877–889.

Irwin, A. R. (2000). Historical case studies: Teaching the nature of science in context. *Science Education, 84*, 5–26.

Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth graders' views of nature of science. *Journal of Research in Science Teaching, 39*(7), 551–578.

Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., & Schwartz, R. S. (2002). Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching, 39*(6), 497–521.

Lincoln, D., & Nord, B. (2014). The expanding universe: Dark energy. *The Physics Teacher, 52*(6), 337–343.

Neumann, K., Boone, W. J., Viering, T., & Fischer, H. E. (2013). Towards a learning progression of energy. *Journal of Research in Science Teaching, 50*(2), 162–188.

Papadouris, N., & Constantinou, C. P. (2014). Distinctive features and underlying rationale of a philosophically-informed approach for energy teaching. In R. F. Chen, A. Eisenkraft, D. Fortus, J. Krajcik, K. Neumann, J. Nordine, & A. Scheff (Eds.), *Teaching and learning of energy in K – 12 education* (pp. 207–221). Cham: Springer.

Papadouris, N., & Constantinou, C. P. (2017). Integrating the epistemic and ontological aspects of content knowledge in science teaching and learning. *International Journal of Science Education, 39*(6), 663–682.

Schwartz, R. S., Lederman, N. G., & Crawford, B. A. (2004). Developing views of nature of science in an authentic context: An explicit approach to bridging the gap between nature of science and scientific inquiry. *Science Education, 88*, 610–645.

Chapter 19
The Use of Digital Technologies to Enhance Learners' Conceptions of Nature of Science

Isha DeCoito

19.1 Scientific and Technological Literacy

Equipping students with scientific and technological literacies and skills is not a separate educational process. Our wired and increasingly digital world brings with it two realities: students know much about the use of digital resources, and such resources in support of many aspects of science instruction are readily available. Dede (2005) reported that emerging learning styles include fluency in multiple media and simulation-based virtual settings, communal learning, experiential learning, guided mentoring and collective reflection, and codesigning learning experiences that are personalized to individual needs and preferences. Emerging learning styles signal that teachers adapt their teaching styles to reflect multimodal ways of conveying understanding. The use of digital technologies in supporting learning has dramatically increased across many disciplines (Annetta et al. 2013; DeCoito and Richardson 2016) and has become a major focus of research during the past decade (Martinez-Garza and Clark 2015). Digital technology offers multimodality that enables students to learn as well as demonstrate an understanding in science (Ng 2010). Of course, the aforementioned is only advantageous for learning if activities utilizing digital technologies are effectively aligned with what is to be learned (DeCoito 2012; Higgins et al. 2012).

In science education, there is a worldwide call for schools to improve students' and teachers' scientific literacy, including improvements in students' and teachers' understanding of science content (i.e., principles, laws, and theories of science), socioscientific issues (i.e., social, political, economic, and moral-ethical issues pertaining to science), nature of science (NOS) (i.e., the philosophy, sociology, and

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_19

methods of science), and scientific and technological problem-solving. It is widely accepted that NOS is an essential element in the development of science and technology literacy (Duschl et al. 2007). Many studies have fostered enhanced NOS teaching and learning (Abd-El-Khalick 2012; Abd-El Khalick and Lederman 2000a). However, research on teachers' and students' understanding of NOS reveal that most curriculum efforts have not met with similar success, and misconceptions concerning NOS abound (Deng et al. 2011). Generally, students' NOS views are deficient, distorted, and confused, and most students leave high school with very simplistic views about the nature and certainty of scientific knowledge and how such knowledge is constructed (Abd-El-Khalick and Lederman 2000b; Kang et al. 2004; Ryder et al. 1999). Students' naïve conceptions of NOS are attributed to a lack of knowledge of this aspect of science (Abd-El-Khalick and Lederman 2000a), which is directly linked to classroom instruction. An important aspect of scientific literacy is an understanding of the chronological development of scientific knowledge, including knowledge of those who contributed to this development, the time periods associated with major inventions and discoveries, and the locations and social and cultural contexts in which key developments occurred. In this chapter, the author discusses the potential of digital scientific timelines and a digital video game in enhancing students' understanding of NOS.

19.1.1 Digital Literacies and Science Education

Educators are faced with the challenge of adapting to an environment where literacies are ever more important. How knowledge is represented is a crucial aspect of knowledge construction. Thus, the mode and media chosen or the form of representation is integral to meaning and learning more generally. The ways in which something is represented shape both what is to be learned, that is, the curriculum content, and how it is to be learned. It follows, then, that to better understand learning and teaching in the multimodal environment of the contemporary classroom, it is essential to explore the ways in which representations in all modes feature in the classroom (Jewitt 2008).

Digital literacy is important for science learning as it (1) assists students to learn more effectively with the range of information and communications technology (ICT)-enabled affordances that have the capacity to motivate and enable a better understanding of science concepts and (2) lessens the working memory's cognitive load, while learning science that is ICT-based (Ng 2011). Webb (2005) maintains that the affordances offered by ICT benefit science learning by promoting cognitive development, highlighting relevance via relating science to students' real-life experiences, increasing students' self-management of their own learning, and facilitating data collection and presentation. One such avenue for achieving the aforementioned goals is through digital timelines.

Previous attempts to improve student conceptions of NOS focused primarily on the development of curricular materials, including History of Science Cases

(Clough et al. 2010), which tended to address NOS implicitly through instruction on inquiry and process skills. In addition, the nature and lack of resources available to teach about NOS were also questioned. For example, a vast majority of science textbooks and Internet websites focusing on science content commonly include features highlighting major discoveries and their discoverers in brief and decontextualized ways – situating discoveries in the framework of pedagogy-based or curriculum-based conceptual development, not chronological/historical development. As a result, students (and teachers) may lose out on the opportunity to experience the context-rich historical narrative of scientific discovery and invention. Furthermore, the expository representations of science in common teaching-learning materials may not provide a realistic depiction of the historical development of some scientific aspect, which occurred over an extended period of time, led by scientists who were influenced by the people, politics, and cultures of their day. Alternatively, modern computer-based digital media provide an opportunity for students and teachers to communicate the development of science through rich multimedia modes of representation. Information and learning materials can be conveyed in a variety of modes for science learning – visual, text, audio, and multimedia.

In this chapter the author reports on two research projects that implemented explicit-reflective instruction for teaching about NOS and focuses broadly on the extent to which the integration of digital technologies impacted teacher candidates' (TCs') NOS conceptions, with specific emphasis on digital scientific timelines and digital games. In addition, the author addresses several key NOS targets (Next Generation Science Standards (NGSS), 2013) categorized in three suites – tools and products of science; science knowledge and science limits; and human elements of science – as the timelines and game explore a combination of these targets, including shared methods, law/theory distinction, tentative, durable and self-correcting, science has limits, creativity, subjectivity, and social and cultural influences.

19.2 Digital Timelines and Video Games

19.2.1 Digital Scientific Timelines

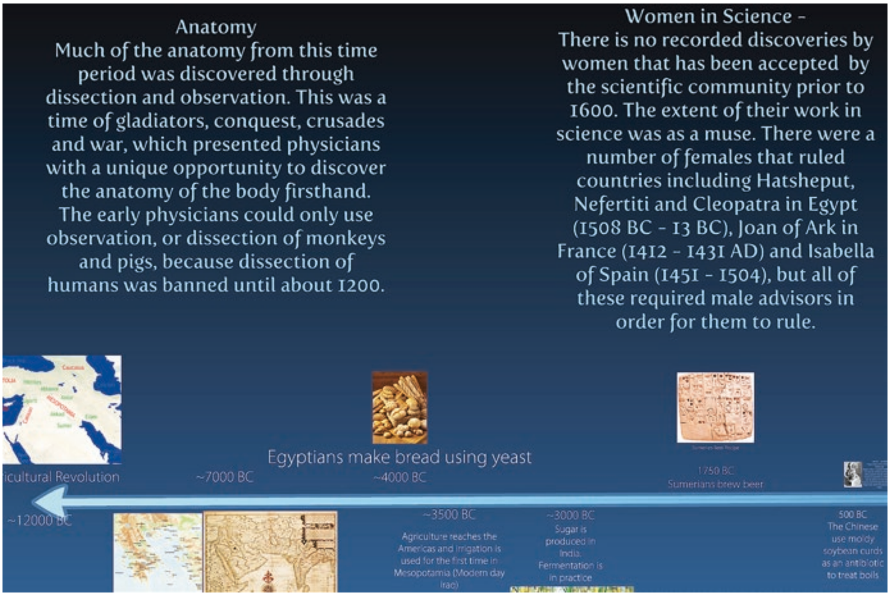
Timelines have been used for some time to explore the historical development of a number of disciplines (Twyman et al. 2006). Unlike traditional timelines, the interactivity of online timelines allows time-scales to vary substantially. Online, interactive timelines can support visually rich displays of information – text, images, multimedia, hyperlinks – using spatial arrangements, categories, and color schemes to convey meaning, which make them ideal platforms for achieving a variety of objectives. This may therefore avoid the common problem in which students encounter bits and pieces of science out of context and unconnected to larger scientific themes and fail to develop a sense of scientific era by connecting individual events to larger movements and themes. These issues may limit students' grasp of science topics but may also restrict students' engagement in critical analysis of the science of a particular era. Interactive timelines, therefore, may help students understand the chronology of scientific events and assist in situating newly encountered events and figures in relation to those previously studied (DeCoito and DiLucia 2014). Furthermore, timelines provide a visual aid for identifying cause-and-effect relationships between events and a visual prompt to activate prior knowledge.

Certainly, timelines may be created in paper-and-pencil formats or interactive computer-based digital formats. While paper-and-pencil timelines invariably tell the story of science through the use of text and static images (DeCoito 2009), digital timelines may include text, images, audio, video, and interactive digital features such as hyperlinks, digital game components, and social networking capabilities. These digital versions provide opportunities for context-rich historical narrative afforded by digital media and the development of students' twenty-first-century skills. Activities of this nature are instrumental in (1) informing students about the life of scientists; (2) assisting students in understanding the origins of science theories, concepts, and widespread practices; and (3) situating science in a historical, cultural, and social context.

In this study, digital timelines were utilized to explore the history of scientific discoveries, including the scientists and technology captured in a time period, using a variety of formats (e.g., Prezi, Movie Maker, and Tiki-Toki). The primary goal of this activity was to validate this strategy with TCs with a goal of enhancing their scientific literacy by requiring them to research, and include in their timelines, not only significant developments in the history of biology/chemistry/physics of a specified period but also pertinent sociocultural information related to the various discoveries and their discoverers. Another goal was for TCs to experience the process of developing and completing digital timelines as a way to inform them about the importance of NOS, which they could then, in turn, implement with secondary science students in their future practices. TCs assumed dual roles – curriculum developers and co-constructors of knowledge – as they designed their digital timelines. The strategy involved TCs' development of digital scientific timelines and instructions included the preparation of a digital-based presentation suitable for inclusion in a continuous scientific timeline, within an assigned period of time (e.g., pre-1600–2014). Each timeline consisted of content based on significant discoveries and inventions that occurred within an assigned era in the history of the discipline (e.g., biology, chemistry, and physics). This included technical/scientific information about the discovery or invention; information about the individuals and groups involved in the discoveries and inventions; relevant particulars about the inventors'/discoverers' personals lives, education, places of study and work, etc.; and information about the sociocultural milieu (including politics, the economy, art, religion, fashion, etc.) during the assigned time period or era. The inclusion of content reflecting inventions and discoveries from all cultures and nationalities, as well as females, is mandatory. Finally, the presentation encompasses a 10-min visually engaging format, with concise explanatory text, audio, interviews, and videos.

In pairs, TCs enrolled in a senior science methods course randomly selected a time period and conducted research on the scientists and discoveries during that period. Class time was provided for research and teacher-conferencing with students. During the teacher conferencing, draft timelines were showcased and discussed. One challenge that was highlighted is the fact that the timelines were too lengthy as learners had a difficult time navigating the information they obtained through their research. Hence, they had to judiciously select key events to include in their timelines. One seminar was dedicated to a gallery walk that showcased all the digital scientific timelines.

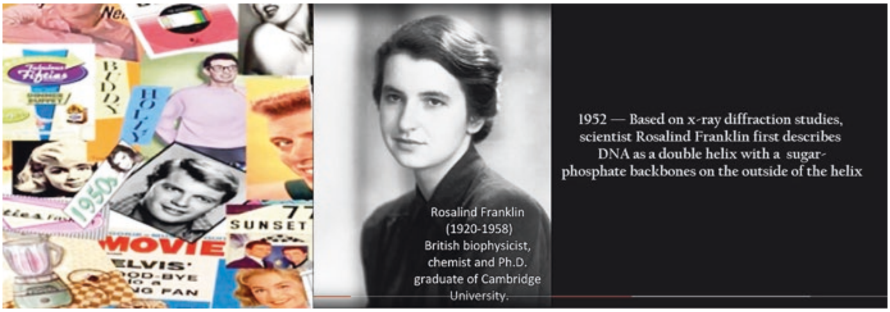
The timelines developed by the learners were interesting, engaging, and informative. In most cases, TCs created their timelines in Prezi, Movie Maker, or Tiki-Toki formats. Figure 19.1 shows a screen capture of a portion of a timeline created in Prezi, a web-based online application. In this timeline, historical information is provided in the form of text captions, photos, diagrams, and YouTube video clips that are arranged in a quasi-linear fashion, providing an engaging visual narrative of the history of biology across various cultures and continents, pre-1600. For example, in this time period, learners showcased the fact that for tens of thousands of years, humans were foragers, yet in a relatively short period of time agricultural systems appeared in several widely separated parts of the Old World and the New World, and by 2000 years ago most human populations were dependent on agriculture. Approximately 7000 BC agriculture reached Southern Europe and India, including the domestication of goats, sheep, and cattle and the production of rice. Around this time, Egyptians made bread using yeast, and around 3500 BC agriculture reached the Americas, and irrigation was used for the first time in Mesopotamia (Modern day Iraq). In 3000 BC, sugar was produced in India, and fermentation came into practice around 1750 BC as Sumerians brew beer. The Chinese used moldy soybean curds as an antibiotic to treat boils in 250 BC, and the Greeks practiced crop rotation to maximize fertility in 1590 BC.



Anatomy
Much of the anatomy from this time period was discovered through dissection and observation. This was a time of gladiators, conquest, crusades and war, which presented physicians with a unique opportunity to discover the anatomy of the body firsthand. The early physicians could only use observation, or dissection of monkeys and pigs, because dissection of humans was banned until about 1200.

Women in Science -
There is no recorded discoveries by women that has been accepted by the scientific community prior to 1600. The extent of their work in science was as a muse. There were a number of females that ruled countries including Hatsheput, Nefertiti and Cleopatra in Egypt (1508 BC - 13 BC), Joan of Ark in France (1412 - 1431 AD) and Isabella of Spain (1451 - 1504), but all of these required male advisors in order for them to rule.

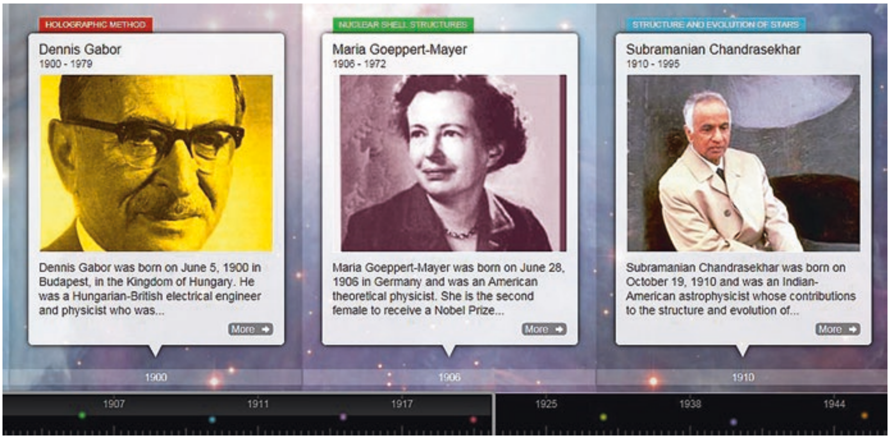
Fig. 19.1 Screenshot from the pre-1600 biology timeline



Rosalind Franklin
(1920-1958)
British biophysicist,
chemist and Ph.D.
graduate of Cambridge
University.

1952 — Based on x-ray diffraction studies, scientist Rosalind Franklin first describes DNA as a double helix with a sugar-phosphate backbones on the outside of the helix

Fig. 19.2 Screen capture of a biology timeline (1950–1959)



Dennis Gabor
1900 - 1979

Dennis Gabor was born on June 5, 1900 in Budapest, in the Kingdom of Hungary. He was a Hungarian-British electrical engineer and physicist who was...

Maria Goeppert-Mayer
1906 - 1972

Maria Goeppert-Mayer was born on June 28, 1906 in Germany and was an American theoretical physicist. She is the second female to receive a Nobel Prize...

Subramanian Chandrasekhar
1910 - 1995

Subramanian Chandrasekhar was born on October 19, 1910 and was an Indian-American astrophysicist whose contributions to the structure and evolution of...

Fig. 19.3 A screen capture of a physics timeline showcasing scientific discoveries (1969–2012)

Figure 19.2 illustrates a portion of a biology timeline created using Movie Maker software, which allows the user to create a moving picture timeline, containing text, still images, movie clips (self-created or imported), and audio file narration. The timeline spanned the 1950s and included, for example, the establishment of the American Institute of Biological Sciences, the lives and contributions of biologists who pioneered cloning procedures, Rosalind Franklin's contribution to the structure of DNA, along with other culturally relevant issues such as Rosa Parks and the Civil Rights Movement and the launch of Sputnik 1 in 1957.

Figures 19.3 and 19.4 are examples of physics (1960–2012) and chemistry timelines (1960–1989) created in Tiki-Toki (https://www.tiki-toki.com/), a web-based software for creating interactive timelines that can be shared on the Internet. Students were able to create different categories for stories and events, images, and YouTube videos, including interviews with famous scientists as well as details of their lives and discoveries.

It is evident that the learner's (or students' or user's or teachers') choice of content to incorporate in the digital timelines was not simple given the enormous

Fig. 19.4 A screen capture of a chemistry timeline showcasing discoveries (1960–1989)

amount of digital resources available online. The screen captures included here do provide evidence of the rich story-like quality of the digital scientific timelines. However, readers were encouraged to look for examples online to see the interactive audio-visual richness that communicate the moving image qualities of the actual timelines that convey highly visual aspects. In terms of creativity, those using this strategy were encouraged to be creative in terms of including audio and YouTube videos, as well as interviews with scientists. Through reflections and interviews, TCs reported a preference for digital timelines over traditional formats as they (1) are more powerful, dynamic, and convenient than traditional (paper and pencil) poster media; (2) showcase learning more effectively; (3) allow for the incorporation of an assortment of topics; (4) promote creativity; (5) encourage collaboration; (6) highlight inquiry; and (7) promote and showcase diversity and inclusivity in science.

Learners appreciated the opportunity to engage in an activity whereby they could situate the historical development of science in the sociocultural contexts in which they occurred – an important aspect in the development of scientific literacy (Millar 2006). Many of the learners indicated that they increased their knowledge about how personalities and culture influenced the development of science. Some learned more about the role of women (and other minorities in the field) in the history of science and about the highly collaborative nature of scientists' work. Overall, TCs learned about science (especially its historical and sociocultural aspects), scientists, and NOS through the preparation and presentation of their digital timelines:

> I learned about the history of the discovery, who the discoverer was, their background, how the discovery came about … how so many different cultures played a role in the history of science … I had to research about various processes and experiments that were conducted by the scientists. This gives me a more complete understanding of the science behind the processes. Science is progressive …

> I learned about their [scientists] background … as children and as scientists. This was cool because you see that scientists are regular people … you can see how their personal lives influence their research, their commitment and dedication … to discover an innovation to help others …

> I learned about how the discoverers made their discoveries, the process they went through (i.e., hypothesizing, testing, etc.). It was also possible to see how the initial discoveries brought about new and better discoveries … science is always evolving. It is dynamic and the focus shifts with different subjects or fields yielding the majority of results and potential implications. It is also collaborative, and credibility does matter …

19.2.2 Digital Video Games (DVGs): The Potential for Learning About NOS

Researchers have found that computer-based games have significant educational value (Dostál 2009; McFarlane et al. 2002) and may help students learn elements of NOS, including the principles, laws, and theories of science (Barab et al. 2007; Clark et al. 2009). Using games, and other strategies, as part of the educational environment fits into the philosophy of active learning and constructivism. McKeachie (1994) claimed that involving students as active participants results in a positive learning experience and explains that learning is enhanced if students make decisions (with teacher guidance) and then assess and evaluate the consequence(s) of each decision. Similarly, Kohn (1997) suggested that in order to promote a deeper understanding of content, students ought to be engaged in their learning. In support of this suggestion, Applefield et al. (2000) and others have reported on the benefits of adopting a more constructivist, student-centered model of teaching and learning. Based on the increased possibilities for learning in and from these environments, it is not surprising that a great deal of attention is being focused on the role of digital games in education. For example, studies on the use of digital games in mathematics, language arts and reading, physics, natural science, and engineering show enhanced learner experiences, development of positive experiences toward subject area, increased student motivation, enhanced learning, improved cognitive outcomes from basic recall to higher level thinking, and improved performance on problem-solving tasks (Conati and Zhao 2004; Foss and Eikaas 2006; Ke 2009; Ravenscroft and Matheson 2002; Yip and Kwan 2006).

Despite literature support for the utilization of digital-based online games in science education (Clark et al. 2009; Martinez-Garza and Clark 2015), discussions on the use of digital games to teach about NOS in preservice secondary science education is limited. The impact and potential afforded by context-rich historical narrative was captured in a study of an interactive digital video game, *History of Biology* (Fig. 19.5). *History of Biology*, developed by Spongelab Interactive (https://www.spongelab.com/), is an interactive online digital game designed to guide senior high school and introductory university/college biology students through concepts about the history of biology, including the lives of scientists, their discoveries, and the impact of their discoveries on our culture, society, politics, economics, and ethics. Starting in the seventeenth century, with the invention of microscopes, and the first descriptions of microscopic life, users complete missions and solve puzzles by researching the lives and scientific discoveries of over 20 scientists. Users progress through 14 stages of a rich storyline-driven game that parallels the scientific time-

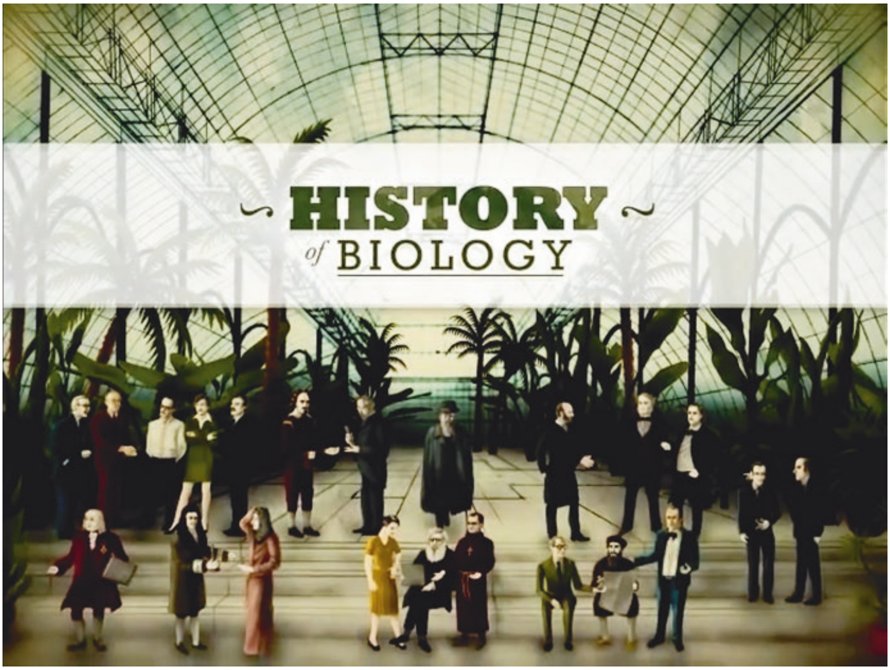
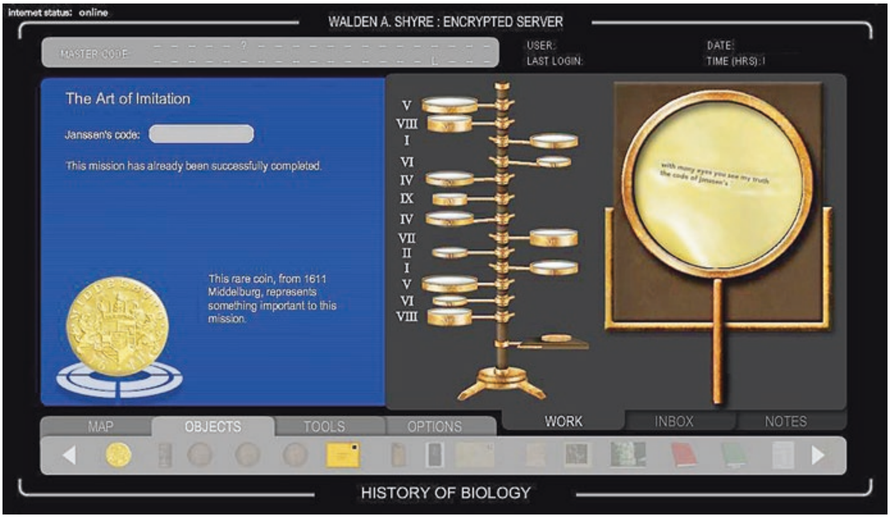


Fig. 19.5 History of biology digital video game trailer cover

line of discovery. Missions are designed to expand players' knowledge of science and foster various twenty-first-century skills including critical thinking, communication, problem-solving, collaboration, creativity, adaptability, initiative, self-direction, information literacy, media literacy, information communication technology (ICT) literacy, and knowledge and skills in core subjects, including English, arts, mathematics, and science. Even as *HoB* creatively has the user access a variety of sites (such as Basic Local Alignment Search Tool (BLAST), which allows a user to input a nucleotide sequence to determine the significant similarities of segments) that they otherwise would not have been aware of on the Internet, the user is required to successfully fulfill tasks in order to move through the programmers' predetermined path. When a mission is not completed, the user is not able to move forward to attempt the next mission.

The game content takes users through cell theory, microscopes (Figs. 19.6 and 19.7), classification, evolution, mechanisms of heredity, the central dogma of genetics, and the genomics revolution. The player must explore both real and fictional websites (Fig. 19.8) to uncover the hidden clues needed to solve the missions and break the master code.

A study was initiated after the author invited the cofounder of Spongelab Interactive to conduct a workshop in the science methods course on the use of online games for teaching and learning in biology. Students were introduced to, and participated in, various digital games, including the Genomics Digital Lab (GDL), an online learning environment where users experience the world of biology through discovery-based learning. Students were briefly introduced to the *History of Biology* game.



USER:
LAST LOGIN:
DATE:
TIME (HRS):

The Art of Imitation

Janssen's code:

This mission has already been successfully completed.

This rare coin, from 1611 Middelburg, represents something important to this mission.

with many eyes you see my truth
the code of Janssen's

Fig. 19.6 An early microscope

USER: jer friedberg
LAST LOGIN: September 4, 2010
DATE: September 5, 2010
TIME (HRS): 00:04:47

Forcing Discovery

The answer to the formula = -

This mission has already been successfully completed.

This vintage wine cork from the Isle of Wight has been passed down through generations

Fig. 19.7 A modern microscope

A study conducted with nine TCs (six females and three males) who volunteered to play *History of Biology* over a 4-month period provides some substantiation of the utility of this game to teach aspects of the nature of science. The research project assumed an explicit-reflective teaching approach from the perspective that *History of Biology* was developed in the context of the history, philosophy, and sociology of science, characteristics of scientific knowledge that result from scientific investigations. Data included NOS questionnaires (DeCoito 2009) consisting of 30 items,

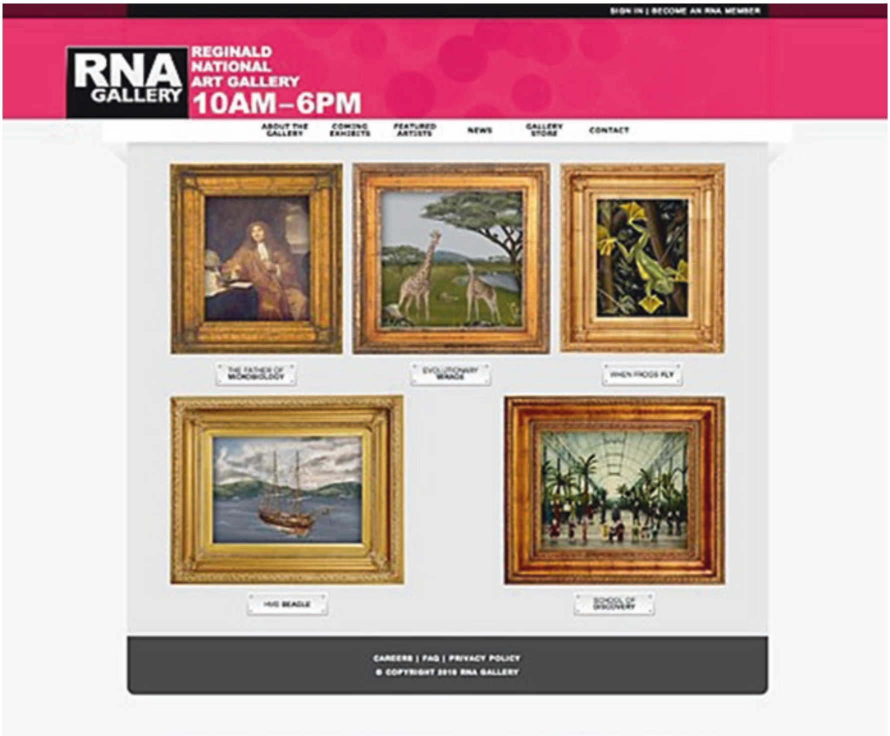


Fig. 19.8 Fictional gallery in the *History of Biology*

which are a list of 30 tenets of NOS, taken verbatim from the literature (Lederman et al. 1998, 2002; Nott and Wellington 1998; Osborne et al. 2003; Schwartz et al. 2004), and had been previously validated in studies related to ascertaining NOS views. Learners' notes related to learning science, learning about science, and doing science were compiled during the game play; and interviews were conducted after game play. The interviews explored changes in students' NOS views, their experiences with digital games in learning and/or teaching, and their experiences with *History of Biology*. Participants' views included several naïve conceptions about NOS prior to instruction. Based on the presurveys, none of the students held well-informed views of all NOS elements (tentativeness, empirical basis, subjectivity, human inference, imagination and creativity, sociocultural embeddedness, and laws and theories), though several did hold adequate views of certain conceptions. Changes in learners' views were particularly evident with regard to tentative NOS, the distinction between observation and inference, the social and cultural NOS, and subjectivity in science. As captured by a learner:

> Scientists try to be as objective as possible but given that everybody gets attached to their research and attached to the subject itself, it's really hard to be objective. Science itself is a very creative process because you always need to come up with different ways to discover something …

Less pronounced changes in participants' views of science were empirical and subjective (theory-laden) and the relationship between theory and law. These findings parallel similar studies on teachers' and students' conceptions of NOS (Akerson et al. 2000; DeCoito 2009). *History of Biology* engaged the users and it also enhanced students' NOS conceptions (DeCoito and Richardson 2016). Teacher candidates ascribed the changes in NOS views to:

(a) Explicit instruction – "Yeah, it's no one thing. Certainly, the instruction was a large factor and the assignments as well, it's all related to the instruction."
(b) *History of Biology* game – "I feel that the game made me think about the ins and outs of science that I didn't realize before … wondering about the scientists and how science did change with history."
(c) Practicum experiences – "I originally thought that science was very factual, and there's a process to things and you have to follow the steps, but in working with my students I realized that they have brought a lot more creativity to it, and they had fun with it and in doing that, they learned a lot more than they necessarily would have using the scientific method."

Explicit instruction, in the form of digital scientific timelines and the digital game, during the methods course was cited as a key factor for influencing NOS views.

Seven of the nine participants completed the game. Some of the challenges included ambiguous instructions and technical aspects associated with navigating through the various levels of the game. Successes included collaboration among TCs, conducting research to find clues, engagement, incorporating everyday components such as Google Maps, and the fact that tasks (quizzes, etc.) were directly related to various components of the game, thus supporting and enhancing learning. TCs overwhelmingly agreed that the game contributed to learning in science as it provides a context for teaching science as well as science content. There was unanimous agreement that the game is effective for teaching and learning about the nature of science:

> … the humanness of scientists is definitely there. Not in every case, because the information comes from online sources too, but in a lot of cases, you learn things you wouldn't have thought about these people, and you find out that they are just people … in that sense the nature of the enterprise, it's not this rigid objective thing. It does talk about the context of a lot of those discoveries and it talks about the ramifications of them too.

Advantages of using the game to teach science included developing problem-solving skills, engaging learners, catering to a variety of learners' needs, improving content knowledge, and learning about NOS. The participants all agreed that they would incorporate digital online games in their future classroom practices as a mode of engaging students and teaching science and NOS, provided that there was access to computers. Disadvantages included access to computers and time to play the game in a classroom. Finally, TCs' motives for participating in the game included seeking ways to incorporate new technologies in the classroom, exploring various strategies to engage students, evaluating the game as a teaching and learning tool, and experiencing *History of Biology* and its potential for teaching and learning in and about science.

19.3 Conclusion

The explicit, reflective instruction about NOS and integration of digital literacies employed in the two studies helped TCs improve their technological and scientific literacy in a purposeful and engaging fashion. An explicit-reflective teaching approach using digital scientific timelines and a digital game to teach students has the potential to make significant contributions to the advancement of science teaching and learning. By providing opportunities for exploring NOS via digital scientific timelines and a DVG, TCs developed positive attitudes toward teaching NOS through digital technologies in the classroom. Overall, participants made substantial gains in their understandings of the target aspects of NOS and can be attributed to a number of factors including explicit-reflective NOS instruction, playing *History of Biology*, and practicum teaching experiences.

Findings also highlight the potential of digital technologies to address NOS targets (Next Generation Science Standards (NGSS), 2013) as the digital timelines and DVG-incorporated shared methods, law/theory distinction, tentative, durable and self-correcting, limitations of science, creativity, subjectivity, and social and cultural influences.

The results of this study raise many issues and questions. Some areas of concern include teachers' NOS conceptions, self-efficacy in terms of incorporating digital technologies judiciously in their practice to address NOS targets, access to the said technologies, and aligning these technologies with curricular orientations. For example, online educational games are neither typically aimed at high school students (Qian 2009) nor are they generally aligned with curriculum. Future studies on digital technologies explored in this chapter could explore a specific topic in science, a cognitive skill, or an age group, and explore how these factors interact with, and contribute to, learning science and NOS. These issues warrant further research in terms of how we envision teaching and learning science and NOS, implications for enhancing scientific and technological literacy, as well as equipping students with twenty-first-century skills. Findings from these studies may contribute to the information available to science and STEM educators and curriculum consultants about integrating digital literacies in science teacher education through activities, products of personal creativity that vary according to students' unique learning styles.

References

Abd-El-Khalick, F. (2012). Examining the sources for our understandings about science: Enduring conflations and critical issues in research on nature of science in science education. *International Journal of Science Education, 34*(3), 353–374.

Abd-El-Khalick, F., & Lederman, N. G. (2000a). The influence of history of science courses on students' views of nature of science. *Journal of Research in Science Teaching, 37*(10), 1057–1095.

Abd-El-Khalick, F., & Lederman, N. G. (2000b). Improving science teachers' conceptions of nature of science: A critical review of the literature. *International Journal of Science Education, 22*(7), 665–701.

Akerson, V. L., Abd-El-Khalick, F. S., & Lederman, N. G. (2000). Influence of a reflective activity-based approach on elementary teachers' conceptions of the nature of science. *Journal of Research in Science Teaching, 37*, 295–317.

Annetta, L. A., Frazier, W. M., Folta, E., Holmes, S., Lamb, R., & Cheng, M. T. (2013). Science teacher efficacy and extrinsic factors toward professional development using video games in a design-based research model: The next generation of STEM learning. *Journal of Science Education and Technology, 22*(1), 47–61.

Applefield, J. M., Huber, R. L., & Moallem, M. (2000). Constructivism in theory and practice: Toward a better understanding. *High School Journal, 84*(2), 35–46.

Barab, S., Sadler, T., Heiselt, C., Hickey, D., & Zuiker, S. (2007). Relating narrative, inquiry, and inscriptions. *Journal of Science Education and Technology, 16*(1), 59–82.

Clark, D., Nelson, B., Sengupta, P., & D'Angelo, C. (2009). *Rethinking science learning through digital games and simulations: Genres, examples, and evidence*. Washington, DC: National Research Council.

Clough, M. P., Herman, B. C., & Smith, J. A. R. (2010, January). *Seamlessly teaching science content and the nature of science: Impact of historical short stories on post-secondary biology students*. Paper presented at the Association for Science Teacher Education (ASTE) National Conference, Sacramento, CA.

Conati, C., & Zhao, X. (2004). *Building and evaluating an intelligent pedagogical agent to improve the effectiveness of an educational game*. Proceedings of IUI '04, international conference on Intelligent User Interfaces, Island of Madeira, Portugal, 6–13.

DeCoito, I. (2009). *Improving teachers' and students' nature of science conceptions- Using reading and writing activities to reflect on the nature of science*. Saarbrücken: Lambert Academic Publishers.

DeCoito, I. (2012). Digital games in science education: Developing students' 21st century learning skills. In Z. Karadag & Y. Devecioglu-Kaymakci (Eds.), *Proceedings of the International Dynamic, Explorative, and Active Learning (IDEAL) conference* (pp. 159–172). Turkey: Bayburt University. ISBN:978-605-61893-4-0.

DeCoito, I., & DiLucia, D. (2014, January). *Integrating technology and developing digital competencies in science education*. Paper presented at the annual meeting of the Association for Science Teacher Education, San Antonio, TX, January 15–18.

DeCoito, I., & Richardson, T. (2016). Focusing on integrated STEM concepts in a digital game. In M. Urban & D. Falvo (Eds.), *Improving K-12 STEM education* (pp. 1–23). Hershey: IGI Global.

Dede, C. (2005). Planning for neomillennial learning styles. *Educause Quarterly, 28*(11), 7–12. www.educause.edu/apps/eq/eqm05/eqmo511.

Deng, F., Chen, D. T., Tsai, C. C., & Chai, C. S. (2011). Students' views of the nature of science: A critical review of research. *Science Education, 95*(6), 961–999.

Dostál, J. (2009). Educational software and computer games – Tools of modern education. *Journal of Technology and Information Education, 1*(1), 24–28.

Duschl, R., Schweingruber, H., & Shouse, A. (Eds.). (2007). *Taking science to school: Learning and teaching science in grades K-8*. Washington, DC: National Academies Press.

Foss, B. A., & Eikaas, T. I. (2006). Game play in engineering education – Concept and experimental results. *International Journal of Engineering Education, 22*(5), 1043–1052.

Higgins, S., Xiao, Z., & Katsipataki, M. (2012). *The impact of digital technology on learning: A summary for the education endowment foundation*. London: EEF.

Jewitt, C. (2008). Multimodality and literacy in school classrooms. *Review of Research in Education, 32*(1), 241–267.

Kang, S., Scharmann, L., & Noh, T. (2004). Examining students' views on the nature of science: Results from Korean 6th, 8th, and 10th graders' views of nature of science. *Science Education, 89*(2), 314–334.

Ke, F. (2009). A qualitative meta-analysis of computer games as learning tools. In R. E. Ferdig (Ed.), *Effective electronic gaming in education* (Vol. 1, pp. 1–32). New York: Information Science Reference.

Kohn, A. (1997, September 3). Students don't 'work'– they learn. In *Education week on the web*. Retrieved September 19, 2018, from http://www.alfiekohn.org/teaching/edweek/ngrp.htm.

Lead States, N. G. S. S. (2013). *Next generation science standards: For states, by states*. Washington, DC: The National Academies Press.

Lederman, N., & Abd-El-Khalick, F. (1998). Avoiding de-natured science: Activities that promote understandings of the nature of science. In W. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 83–126). Dordrecht: Kluwer.

Lederman, N., Adb-El-Khalick, F., Bell, R. L., & Schwartz, R. S. (2002). Views of nature of science questionnaire: Towards valid and meaningful assessment of learners' conceptions of the nature of science. *Journal of Research in Science Teaching, 39*(6), 497–521.

Martinez-Garza, M., & Clark, D. B. (2015). Games for learning. In R. Gunstone (Ed.), *Encyclopedia of science education* (pp. 1–4). Dordrecht: Springer Netherlands.

McFarlane, A., Sparrowhawk, A., & Heald, Y. (2002). *Report on the educational use of games*. Cambridge: Teachers Evaluating Educational Multimedia, TEEM.

McKeachie, W. (1994). *Teaching tips: Strategies, research, and theory for college and university teachers*. Lexington: D.C. Heath and Company.

Millar, R. (2006). Twenty first century science: Insights from the design and implementation of a scientific literacy approach in school science. *International Journal of Science Education, 28*(13), 1499–1521.

Ng, W. (2010). Empowering students to be scientifically literate through digital literacy. In S. Rodrigues (Ed.), *Multiple literacy and science education: ICTs in formal and informal learning environments* (pp. 11–31). Hershey: Global Publishing.

Ng, W. (2011). Why digital literacy is important for science teaching and learning. *Teaching Science, 57*(4), 26–32.

Nott, M., & Wellington, J. (1998). Eliciting, interpreting and developing teachers' understandings of the nature of science. *Science & Education, 7*(6), 579–594.

Osborne, J. F., Ratcliffe, M., Collins, S., Millar, R., & Duschl, R. (2003). What 'ideas-about-science' should be taught in school science? A delphi study of the 'Expert' community. *Journal of Research in Science Teaching, 40*(7), 692–720.

Qian, Y. (2009). An investigation of current online educational games. In R. E. Ferdig (Ed.), *Effective electronic gaming in education* (Vol. 1, pp. 67–82). New York: Information Science Reference.

Ravenscroft, A., & Matheson, M. P. (2002). Developing and evaluating dialogue games for collaborative e-learning interaction. *Journal of Computer Assisted Learning, 18*(1), 93–102.

Ryder, J., Leach, J., & Driver, R. (1999). Undergraduate science students' images of science. *Journal of Research in Science Teaching, 36*(2), 201–219.

Schwartz, R. S., Lederman, N. G., & Crawford, B. A. (2004). Developing views of nature of science in an authentic context: An explicit approach to bridging the gap between nature of science and scientific inquiry. *Science Teacher Education, 88*(4), 610–645.

Twyman, T., McCleery, J., & Tindal, G. (2006). Using concepts to frame history with explicit instruction. *Journal of Experimental Education, 74*(4), 331–349.

Webb, M. (2005). Affordances of ICT in science learning: Implications for an integrated pedagogy. *International Journal of Science Education, 27*(6), 705–735.

Yip, F., & Kwan, A. (2006). Online vocabulary games as a tool for teaching and learning English vocabulary. *Educational Media International, 43*(3), 233–249.

Chapter 20
Using Exemplars to Improve Nature of Science Understanding

Jennifer C. Parrish, Grant E. Gardner, Cindi Smith-Walters, and Bridget K. Mulvey

20.1 Introduction

For decades, NOS has been recognized as an important component of science education reform (AAAS 1993; NRC 1996, 2011) and has been a major focus in science teacher education (Clough 2007; Lederman and Abd-El-Khalick 1998; McComas and Olson 1998). Research has shown that unless teachers engage in professional development that explicitly addresses NOS conceptions and provides opportunities for reflection, they are not likely to develop views more aligned with science reform recommendations (Abd-El-Khalick and Lederman 2000; Akerson and Hanuscin 2007; Burton 2013; Morrison et al. 2009). While working with teachers, we noticed that those unfamiliar with NOS literature were surprised to learn of the many resources available to support their development of NOS conceptions. This led to the development of the *NOS Example Strategy.* In this four-step instructional strategy, teacher-learners create or use premade NOS Guides. Then, they examine learners' ideas about NOS and negotiate examples to promote reflection. In this chapter, we will first describe how to facilitate teachers' creation of the NOS Guides. Then we will describe how the NOS Example Strategy promotes reflection.

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_20

20.2 An Explicit and Reflective Approach to Teacher Professional Growth for NOS

One of the most effective means to improve teachers' understanding of NOS is to use an approach that is both explicit and reflective (ER). By *explicit* we mean that the targeted NOS subdomains are intentionally brought to the attention of teacher-learners. This can be done in numerous ways, such as through discussion, questioning, or reading about NOS. By *reflective* we mean that teacher-learners actively engage in critical thought in which they carefully consider their existing beliefs about NOS with reference to new information (Dewey 1910). Reflection can occur in a multitude of ways, such as through whole-class or small-group discussion, reflective journaling, or "minds-on" activities like concept mapping. Due to these considerations, including explicit NOS information and providing time for reflection were central in the development of the NOS Example Strategy.

The NOS subdomains articulated in the introduction of this book provide a useful conceptual framework to organize essential NOS concepts appropriate for use in professional development settings. The NOS Example Strategy purposely separates NOS into these discrete subdomains to provide teachers who may hold less sophisticated NOS views with a clear, accessible starting point to begin developing their ideas (Kampourakis 2016). The subdomains specifically targeted in our work include scientific knowledge as (1) tentative, yet durable and self-correcting; (2) empirically based; (3) subjective; (4) sharing methods but having no single, stepwise plan; and (5) a product of human creativity and inference. These subdomains are interconnected and teacher-learners who make more connections among them may hold more sophisticated NOS views (Ozgelen et al. 2013). However, while the NOS Example Strategy primarily serves as an introduction to discrete subdomains, it can be tailored to further challenge teachers with more sophisticated understandings (Fig. 20.1).

20.2.1 Step 1: Create or Use Premade NOS Guides

NOS Guides provide an explicit introduction to NOS subdomains. The guides are the standard we want teachers to aspire toward as they engage in the strategy. The NOS Example Strategy begins by providing teacher-learners with the opportunity to describe their current views about the NOS subdomain. Next, they become familiar with the expert-like views espoused in NOS literature. Guides can be created by teacher-learners or can be partially or fully prepared in advance by professional development or course instructors. Many of our teacher-learners were unaware that NOS ideas were explicitly present in science reform documents. This guided our use of information from the National Science Teacher Association (NSTA), the Next Generation Science Standards (NGSS), and resources commonly used by

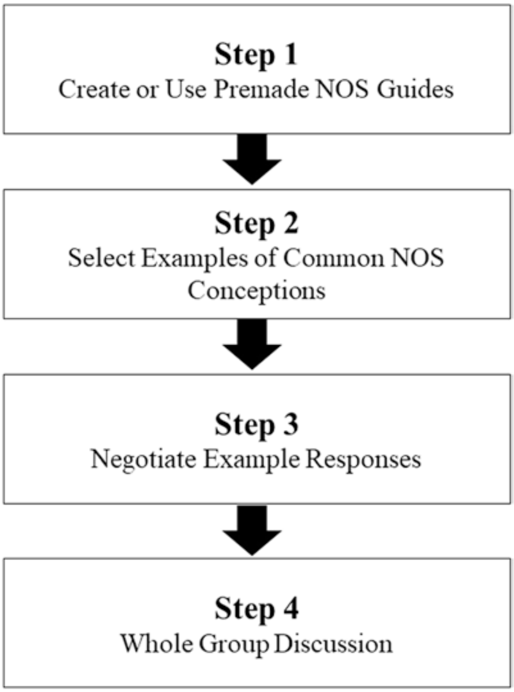


Fig. 20.1 The four-step NOS Example Strategy

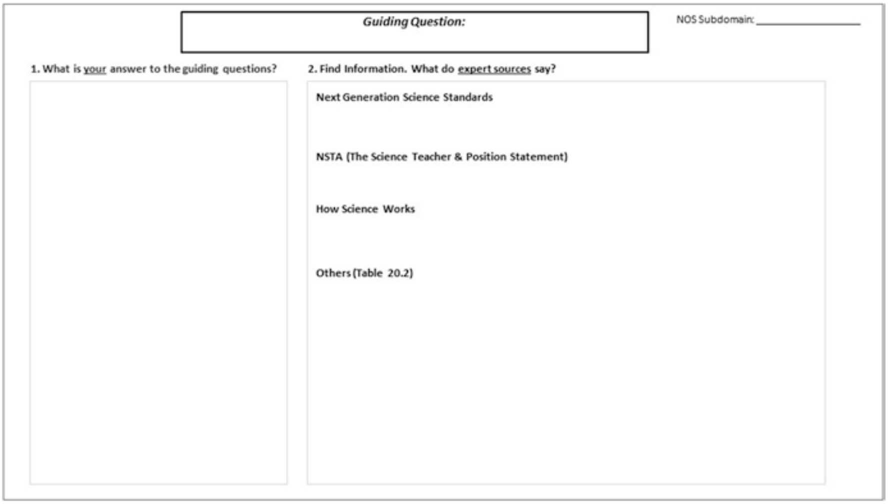
teachers to construct the premade NOS Guides available at the end of this chapter. However, a rich variety of resources can be used (Table 20.2).

We find using premade NOS Guides useful when there are time constraints, but teacher-learners of all NOS understanding levels benefit from creating their own guides. We recommend teacher-learners initially create the guides alone. To create guides one subdomain at a time, individual teacher-learners are provided with a two-column NOS Guide template (Fig. 20.2). Central to the guides are key guiding questions (Table 20.1) that direct attention to the germane NOS subdomain. We recommend using questions by Clough (Chap. 15) and Peters-Burton and Burton (Chap. 9). The first column of the NOS Guide directs teacher-learners to share their ideas by answering the guiding question(s). This is meant to promote teacher thinking rather than some version of memorization about the NOS subdomain (Clough 2007). The second column (Fig. 20.2) provides teacher-learners with an opportunity to explore what expert sources say about the subdomain. The selected NOS literature should be printed or provided electronically to teacher-learners to complete the second column of the NOS Guide. Teachers more familiar with NOS ideas can be challenged through the inclusion of more complex and/or more NOS literature (see Table 20.2 for suggestions).

Table 20.1 Guiding questions for NOS subdomains

NOS subdomain	Sample guiding question(s)[a]
Scientific knowledge is tentative, durable, and self-correcting	Why is well-established science knowledge often so durable and enduring? Regardless of how durable well-established science ideas may be, why is all science knowledge potentially open to revision or even rejection by the scientific community? How is the possibility of revisiting and revising previously established ideas a strength of science? How can scientific knowledge be believed if it keeps changing over time?
Scientific knowledge is empirically based	To what extent is scientific knowledge based on and/or derived from observations of the natural world? In what ways is it based on reasons other than observational and experimental evidence?
Science has subjective and objective elements	To what extent are scientists and scientific knowledge objective and subjective? To what extent can subjectivity be reduced or eliminated?
Science shares methods but no single step-wise plan	How does the notion of a single, step-wise scientific method distort how science actually works? In what ways are particular aspects of scientists' work guided by existing knowledge and protocols?
Creativity in science is vital; scientific knowledge is based on observations and inferences	How are observations and inferences different? To what extent is scientific knowledge the product of human inference, imagination, and creativity? What factors moderate imagination and creativity in the development and justification of science ideas?

[a] Note. Guiding questions are directly from Clough, M. P. (Chap. 15) and Peters-Burton & Burton (Chap. 9). Used with permission



Guiding Question:

NOS Subdomain: ______________

1. What is <u>your</u> answer to the guiding questions?

2. Find Information. What do <u>expert sources</u> say?

Next Generation Science Standards

NSTA (The Science Teacher & Position Statement)

How Science Works

Others (Table 20.2)

Fig. 20.2 An example of a NOS Guide template

Table 20.2 Suggested NOS literature to help teacher-learners construct NOS Guides

Type	Source
Teacher association position statements	NSTA Position Statement on NOS 2000, retrieved from http://www.nsta.org/about/positions/natureofscience.aspx
Publications for teaching NOS	National Academy Press (1998). *Teaching about evolution and the nature of science*. Washington: DC
NOS articles	McComas (1996). Ten myths of science: Reexamining what we think we know about the nature of science. *School Science and Mathematics, 96*(1), 10–16
	McComas (2004). Keys to teaching the nature of science: Focusing on the nature of science in the science classroom. *The Science Teacher, 71*(9), 24–27
	Lederman, J., Lederman, N., Bartos, S., Bartels, S., Antink Meyer, A., & Schwartz, R. (2014). Meaningful assessment of learners' understandings about scientific inquiry – the views about scientific inquiry (VASI) questionnaire. *Journal of Research in Science Teaching, 51*(1), 65–83
	Clough, M. (2018). Framing and teaching nature of science questions (Chap. 15)
	Lederman, N., Abd-El-Khalick, F., Bell, R., & Schwartz, R. (2002). Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching, 39*, 497–521
	Osborne, J., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. (2003). What "ideas –about-science" should be taught in school science? A Delphi study of the expert community. *Journal of Research in Science Teaching, 40*, 692–720
Online NOS resources	Project inquiry, context, and nature of science (ICAN) 2006 annual report. <https://science.iit.edu/mathematics-science-education/resources/lederman-depository/what-nature-science>
	Understanding science. (2017). University of California Museum of paleontology. http://www.understandingscience.org
	The story behind the science <https://www.storybehindthescience.org>

Each NOS Guide, whether created by teacher-learners or premade, elicits teachers' prior knowledge and provides a description representative of an "expert-like" view for one NOS subdomain. Any guides created by teacher-learners should be reviewed by the professional development or course instructor before the end of Step 1.

During the last part of Step 1, we prompt teacher-learners to read and discuss their NOS Guide with a partner. Provide more time for this step if using premade guides. Often, we prefer to engage in a whole group discussion to voice questions about the NOS subdomain. This provides a structured opportunity for the professional development or course instructor to formatively assess participants' NOS ideas and for teacher-learners to reflect collaboratively. For example, while examining the NOS Guide for the subdomain *science shares many methods and there is no single step-wise plan*, one teacher shared, "I am having a difficult time with this idea. I can't think of a time where [my students and I] have used something other than *the* scientific method printed on the poster in my room." Other teachers voiced similar ideas, but then referred back to the NOS Guide. This prompted a discussion about the methods of science presented in one of the suggested resources, *Understanding Science* (provided in Table 20.2). This source focused on how scientific inquiries are not conducted in a step-wise manner or always use a traditional experimental method.

If time constraints are a concern but you want teachers to benefit from creating NOS Guides, teacher-learners can work together in small groups of three to four. Alternatively, or in addition, participants can complete guides outside of face-to-face meeting times. Other modifications could include creating guides focused on NOS instruction (e.g., activities from Lederman & Abd-El-Khalick 1998) or contextualizing NOS using science concepts (e.g., Akerson et al. 2007).

20.2.2 Step 2: Select Examples of Common NOS Conceptions

Next, the professional development or course instructor selects NOS responses from a pool of options that represent common conceptions of specific NOS subdomains. While others have used common conceptions of NOS to promote teacher reflection (see Cobern and Loving 1998), the NOS Example Strategy uses examples of NOS thinking from one of the most widely used survey instruments to assess NOS understandings, the Views of Nature of Science (VNOS) questionnaire (Lederman et al. 2002). The VNOS provides examples of NOS responses in authentic teacher-learner or student language. For example, a question on the VNOS asks, "After scientists have developed a scientific theory (e.g., atomic theory, evolution theory), does that theory ever change?" (VNOS Version D). This question aims to elicit respondents' views regarding the tentative, durable, and self-correcting nature of scientific knowledge. Responses A, B, and C below exemplify common statements from the VNOS survey.

Response A: Scientific knowledge may change in the future. Scientists are always discovering new things. Finding more details, evidence, and proving themselves wrong to find answers. Evolution is an example of this, they are always finding new evidence.

Response B: Scientific knowledge may change in the future because scientists are always learning new things that counter or disprove certain things. Some things are concrete and absolute, others are up to opinion.

Response C: Scientific knowledge does not change in the future. Once scientists publish information, like in textbooks, it is true and does not change completely.

As seen above, we selected three example responses for this NOS subdomain. One response represents an adequate view (Response A), one an inadequate view (Response C), and one a combination of both an adequate and inadequate view

Table 20.3 Sources for example responses

Author(s) and years	Study
Abd-El-Khalick (2005)	Developing deeper understandings of nature of science: The impact of a philosophy of science course on preservice science teachers' views and instructional planning. *International Journal of Science Education, 27*(1), 15–42
Akerson, Hanson, and Cullen (2007)	The influence of guided inquiry and explicit instruction on K-6 teachers' views of nature of science. *Journal of Science Teacher Education, 18*, 751–772
Akerson and Hanuscin (2007)	Teaching nature of science through inquiry: Results of a 3-year professional development program. *Journal of Research in Science Teaching, 44*, 653–680
Akerson, Abd-El-Khalick, and Lederman (2000)	Influence of a reflective activity-based approach on elementary teachers' conceptions of nature of science. *Journal of Research in Science Teaching, 37*(4), 295–317
Akerson, Buzzelli, and Donnelly (2008)	Early childhood teachers' views of nature of science: The influence of intellectual levels, cultural values, and explicit reflective teaching. *Journal of Research in Science Teaching, 45*, 748–770
Bell, Mulvey, and Maeng (2016)	Outcomes of nature of science instruction along a context continuum: Preservice secondary science teachers' conceptions and instructional rationales. *International Journal of Science Education, 38*, 493–520
Donnelly and Argyle (2011)	Teachers' willingness to adopt nature of science activities following a physical science professional development. *Journal of Science Teacher Education, 22*, 475–490
Kucuk (2008)	Improving preservice elementary teachers' views of the nature of science using explicit-reflective teaching in a science, technology, and society course. *Australian Journal of Teacher Education, 33*(2), 16–40
Lederman, Abd-El-Khalick, Bell, and Schwartz (2002)	Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching, 39*, 497–521
Matkins, Bell, Irving, and McNall (January, 2002)	*Impacts of contextual and explicit instruction on preservice elementary science teachers' understandings of the nature of science.* In proceedings of the annual international conference of the Association for the Education of teachers in science, Charlotte, NC
Mesci and Schwartz (2016)	Changing preservice science teachers' views of nature of science: Why some conceptions may be more easily altered than others. *Research in Science Education, 47*, 329–351
Morrison, Raab, and Ingram (2009)	Factors influencing elementary and secondary teachers' views on the nature of science. *Journal of Research in Science Teaching, 46*(4), 384–403
Mulvey and Bell (2017)	Making learning last: Teachers' long-term retention of improved nature of science conceptions and instructional rationales. *International Journal of Science Education, 39*, 1–24
Pelin and Sengul (2012)	Teaching nature of science by explicit approach to the preservice elementary science teachers. *Elementary Education Online, 11*(1), 118–136
Rudge, Cassidy, Fulford, and Howe (2014)	Changes observed in views of nature of science during a historically based unit. *Science and Education, 23*, 1879–1909

(continued)

Table 20.3 (continued)

Author(s) and years	Study
Schwartz, Lederman, and Crawford (2004)	Developing views of science in an authentic context: An explicit approach to bridging the gap between nature of science and scientific inquiry. *Science Education, 88*(4), 610–645
Seung, Bryan, and Butler (2009)	Improving preservice middle grades science teachers' understanding of the nature of science using three instructional approaches. *Journal of Science Teacher Education, 20*, 157–177

(Response B). While we usually select responses from our own work using the VNOS, responses can be culled from many sources (Table 20.3). As few as three or as many as six example responses can be selected for each subdomain. Each example response should be printed as a card for teacher-learners to use in Step 3. To support multiple uses, print the example responses on cardstock and laminate before cutting. Example responses for each subdomain are provided at the end of this chapter.

20.2.3 Step 3: Teacher-Learner Negotiation of Example Responses

Divide teachers into small groups of two to four. Each teacher-learner should have their own NOS Guide for the targeted subdomain. Give each small group a set of laminated example response cards and a continuum line. The continuum line reads "Less like information in NOS Guide" on the left and "More like information in NOS Guide" on the right (Fig. 20.3). Alternatively, teacher-learners could recreate the continuum line on a large white board or piece of paper.

Teachers examine the example responses collaboratively and negotiate whether each response is *more* or *less* representative of the NOS subdomain as described in the NOS Guide. For example, Response C from Step 2 stated that scientific knowledge does not change in the future. This reflects a view of the NOS subdomain that is less like the NOS Guide. Through group members' negotiation with each other, groups use the NOS Guide to reflect on and justify their card locations. They are asked to write a one- to two-sentence explanation on a large sticky note to explain how the example response aligns or conflicts with the expert-like NOS view, placing the note below each example response. This act of categorizing and justifying requires teacher-learners to reflect on the NOS ideas in each response card in light of the expert-like NOS views described in the NOS Guides. If the example responses are laminated, participants can underline or write comments on the cards. As teachers place example responses along the continuum, the instructor should circulate and ask probing questions to formatively assess understandings of the NOS subdomain and increase critical thinking.

LESS like NOS Guide **SOMEWHAT** like NOS Guide **MORE** like NOS Guide

Fig. 20.3 The NOS Example Strategy continuum line

20.2.4 Step 4: Whole Group Discussion

Once members of all groups have placed their cards and added rationales, teacher-learners do a gallery walk around the room. The goal is for teachers to compare groups' card placements and rationales. This provides the professional development or course instructor with a quick formative assessment to guide discussion about the particular NOS subdomain. If there are numerous discrepancies in the card placements in the whole group or class, revisit the NOS Guide and engage in a whole group discussion to try to come to a consensus.

20.3 Influence of the NOS Example Strategy on NOS Conceptions

The four-step NOS Example Strategy has shown promise in improving teachers' conceptions of NOS subdomains, even when teachers initially held inadequate NOS views (Parrish 2017). The most noted benefit was that the NOS Guides provided an opportunity for teachers to make meaning of NOS ideas. Teachers have described the process of completing the NOS Example Strategy as helpful "forced reflection." They needed to think critically about whether the NOS views espoused in example responses were similar to the views presented in the NOS Guides. Placing the example responses along the continuum also required teachers to negotiate with one another and confront their existing —and oftentimes inadequate—views. This is exemplified in the following exchange between an experienced biology teacher and a professional development instructor while piloting the NOS Example Strategy. In this instance, examples were pulled from the VNOS responses of the teacher's high school students. To target the subdomain *science shares multiple methods and there is no single, step-wise scientific method*, students were asked, "Do you think that scientific investigations can follow more than one method?" Three students responded:

Student A: There isn't any one way to do anything. If we only did use one method, then that would just limit the knowledge we could attain. But the beginning and end are the same - starts with a question ends with an answer even if we can't find it because that will be our answer.

Student B: Scientists take answered and unanswered questions and use different methods to test their questions.

Student C: Scientists can decide and investigate using the scientific method to help them with research and keep things organized and in order. The scientific method is the only way for experiments and doing research.

Then, in a one-on-one coaching session, the professional development instructor asked the teacher to reflect on her students' responses:

Teacher: This response looks like mine [points to Response C]. This is a student, right?

Instructor: Yes, this is one of your students. How would you rate each of these students' understandings based on the NOS Guide we just discussed?

Teacher: Response C looks like what I would answer. OK. Hang on. Am I basing it on this [points to NOS Guide] or how do I word it, basic science curriculum that I teach in my classroom?

Instructor: How about you tell me both? That would be a great comparison.

Teacher: The basic way is going to tell you the purpose, research, you know. That's what we teach them and what they see on assessments. It is what is in textbooks. If I base this student response [Response C] on the school's definition [pause], it is different from this [points to the NOS Guide].

This teacher reflected on the discrepancy between information from the NOS Guide and the "textbook" science perspective. They recognized their views about this NOS subdomain were similar to student Response C. After reexamining the NOS Guide, they moved this response toward the "less" like end of the continuum even though initially they thought this NOS response was congruent with science standards documents. This cognitive conflict fostered careful reflection on their currently held conceptions of "the scientific method" and the recommended conceptualizations of this NOS subdomain presented explicitly in the NOS Guide.

20.4 Conclusion

> The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly. – David Ausubel (1968)

Decades of research on NOS teaching and learning have generally agreed that teachers' knowledge about NOS does not align with what we would like learners to understand (N. G. Lederman and Lederman 2014). The NOS Example Strategy provides a way to explicitly present NOS ideas to teacher-learners. Also, it provides an avenue for teacher reflection on specific NOS subdomains through the exchange of ideas regarding example responses. Providing opportunities for teachers to reflect on their own and their students' understandings of NOS is a necessary aspect of teacher preparation and professional development. Using authentic teacher and student responses from the VNOS survey promotes teachers' awareness of both their and their students' existing NOS conceptions. This serves as an introduction to interpretation of assessment results for teachers. It is important to note that teacher-learners need explicit support to develop and interpret results of classroom NOS assessments.

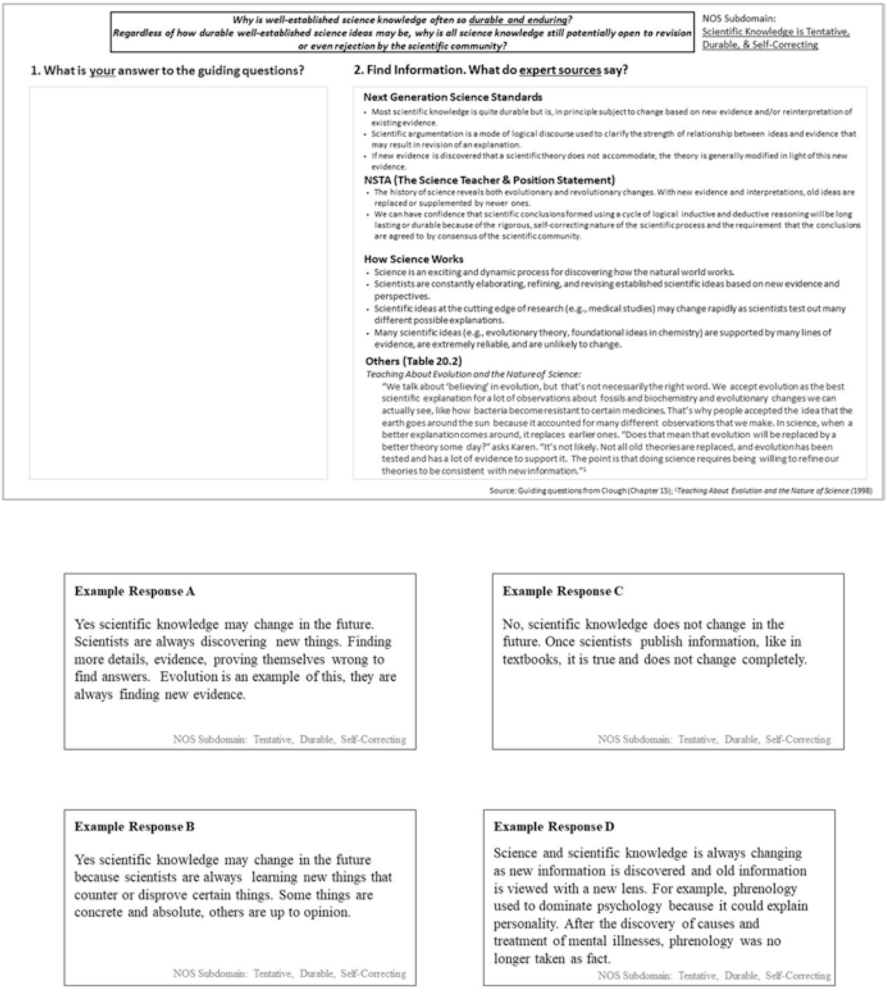
The NOS Example Strategy can be used in a variety of instructional settings to facilitate structured teacher reflection. The strategy could serve as a valuable resource for teacher educators who provide teacher training or professional development. The guides can be tailored to the learning goals of varied science learning contexts. We have used the NOS Example Strategy with success in diverse settings: methods and content courses for preservice teachers, professional development with inservice teachers, and a graduate course for doctoral students about the nature of scientific and mathematical knowledge. When working with teachers in the context of a methods or science content course, we used example responses of learners in the grade band they will teach or are currently teaching. While inservice teachers' use of responses by their own students required a researcher to administer and select students' VNOS example responses, the effort was worthwhile as it provided teachers with authentic examples and served as a means for teachers to formatively assess their students NOS understandings as they reflected on their own. In addition, during follow-up interviews, teachers who used their own students' example responses stated that they would consider using the NOS Example Strategy with their own students (Parrish 2017).

The work presented here requires the professional development or course instructor to have extensive NOS knowledge and familiarity with the extant literature. However, our work collaborating with science teacher educators less familiar with NOS ideas showed that the NOS Example Strategy enabled them to reflect on and improve their own conceptions. When used together, the NOS Guides and example responses make NOS thinking visible and allow science teacher educators to formatively assess what learners already know while they themselves develop more sophisticated understandings.

We acknowledge the NOS Example Strategy as presented in this chapter is not connected to specific science content, making it a decontextualized pedagogical approach to develop NOS conceptions. However, the NOS Example Strategy can be contextualized. When used in a science course for preservice elementary teachers, the instructor had teacher-learners construct NOS Guides one at a time over the course of the semester, specifically when a NOS subdomain could be contextualized in the science content. Use of the NOS Example Strategy in this manner may be ideal since using a combination of decontextualized and contextualized NOS activities is an effective way to improve NOS conceptions (Clough 2006; Mulvey and Bell 2016).

NOS conceptions can be resistant to change despite engagement in explicit and reflective strategies (Akerson et al. 2009; Clough 2006). As such, the NOS Example Strategy may be enhanced by integrating the strategy with other ER approaches, specifically those which include metacognitive components (e.g., concept mapping, reflective journaling) shown to be effective in changing NOS conceptions (Abd-El-Khalick and Akerson 2004, 2009; Akerson et al. 2006). Using the NOS Guides, NOS resources, and example responses represent one way to make NOS ideas explicit and encourage teachers to reflect on NOS ideas. This is key to develop their own understanding of these important science ideas and may help teachers to plan for and assess NOS ideas in their own classrooms.

Premade NOS Guides and Exemplar Responses (Figs. 20.4, 20.5, 20.6, 20.7, and 20.8)



Why is well-established science knowledge often so durable and enduring?
Regardless of how durable well-established science ideas may be, why is all science knowledge still potentially open to revision or even rejection by the scientific community?

NOS Subdomain:
Scientific Knowledge is Tentative, Durable, & Self-Correcting

1. What is your answer to the guiding questions?

2. Find Information. What do expert sources say?

Next Generation Science Standards

- Most scientific knowledge is quite durable but is, in principle subject to change based on new evidence and/or reinterpretation of existing evidence.
- Scientific argumentation is a mode of logical discourse used to clarify the strength of relationship between ideas and evidence that may result in revision of an explanation.
- If new evidence is discovered that a scientific theory does not accommodate, the theory is generally modified in light of this new evidence.

NSTA (The Science Teacher & Position Statement)

- The history of science reveals both evolutionary and revolutionary changes. With new evidence and interpretations, old ideas are replaced or supplemented by newer ones.
- We can have confidence that scientific conclusions formed using a cycle of logical inductive and deductive reasoning will be long lasting or durable because of the rigorous, self-correcting nature of the scientific process and the requirement that the conclusions are agreed to by consensus of the scientific community.

How Science Works

- Science is an exciting and dynamic process for discovering how the natural world works.
- Scientists are constantly elaborating, refining, and revising established scientific ideas based on new evidence and perspectives.
- Scientific ideas at the cutting edge of research (e.g., medical studies) may change rapidly as scientists test out many different possible explanations.
- Many scientific ideas (e.g., evolutionary theory, foundational ideas in chemistry) are supported by many lines of evidence, are extremely reliable, and are unlikely to change.

Others (Table 20.2)

Teaching About Evolution and the Nature of Science:

"We talk about 'believing' in evolution, but that's not necessarily the right word. We accept evolution as the best scientific explanation for a lot of observations about fossils and biochemistry and evolutionary changes we can actually see, like how bacteria become resistant to certain medicines. That's why people accepted the idea that the earth goes around the sun because it accounted for many different observations that we make. In science, when a better explanation comes around, it replaces earlier ones. "Does that mean that evolution will be replaced by a better theory some day?" asks Karen. "It's not likely. Not all old theories are replaced, and evolution has been tested and has a lot of evidence to support it. The point is that doing science requires being willing to refine our theories to be consistent with new information."[1]

Source: Guiding questions from Clough (Chapter 15); [1]*Teaching About Evolution and the Nature of Science* (1998)

Example Response A

Yes scientific knowledge may change in the future. Scientists are always discovering new things. Finding more details, evidence, proving themselves wrong to find answers. Evolution is an example of this, they are always finding new evidence.

NOS Subdomain: Tentative, Durable, Self-Correcting

Example Response C

No, scientific knowledge does not change in the future. Once scientists publish information, like in textbooks, it is true and does not change completely.

NOS Subdomain: Tentative, Durable, Self-Correcting

Example Response B

Yes scientific knowledge may change in the future because scientists are always learning new things that counter or disprove certain things. Some things are concrete and absolute, others are up to opinion.

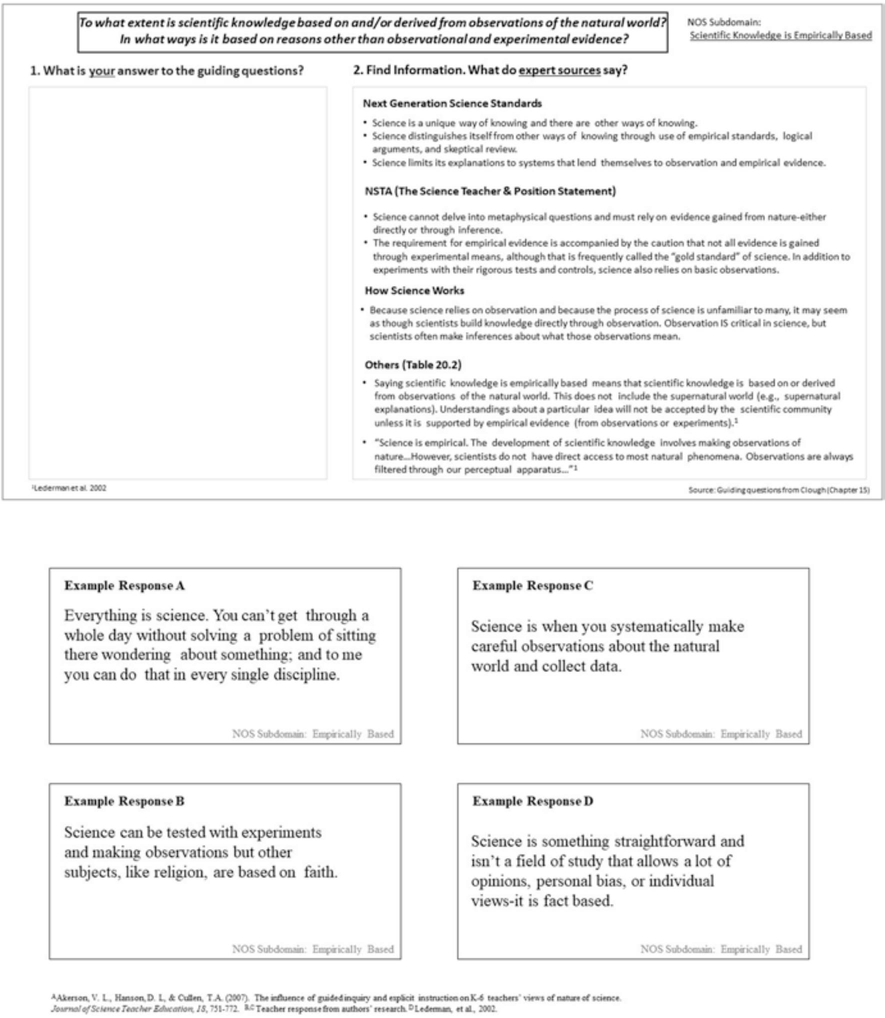
NOS Subdomain: Tentative, Durable, Self-Correcting

Example Response D

Science and scientific knowledge is always changing as new information is discovered and old information is viewed with a new lens. For example, phrenology used to dominate psychology because it could explain personality. After the discovery of causes and treatment of mental illnesses, phrenology was no longer taken as fact.

NOS Subdomain: Tentative, Durable, Self-Correcting

Fig. 20.4 Science is tentative, durable, and self-correcting



To what extent is scientific knowledge based on and/or derived from observations of the natural world?
In what ways is it based on reasons other than observational and experimental evidence?

NOS Subdomain:
Scientific Knowledge is Empirically Based

1. What is your answer to the guiding questions?

2. Find Information. What do expert sources say?

Next Generation Science Standards

- Science is a unique way of knowing and there are other ways of knowing.
- Science distinguishes itself from other ways of knowing through use of empirical standards, logical arguments, and skeptical review.
- Science limits its explanations to systems that lend themselves to observation and empirical evidence.

NSTA (The Science Teacher & Position Statement)

- Science cannot delve into metaphysical questions and must rely on evidence gained from nature-either directly or through inference.
- The requirement for empirical evidence is accompanied by the caution that not all evidence is gained through experimental means, although that is frequently called the "gold standard" of science. In addition to experiments with their rigorous tests and controls, science also relies on basic observations.

How Science Works

- Because science relies on observation and because the process of science is unfamiliar to many, it may seem as though scientists build knowledge directly through observation. Observation IS critical in science, but scientists often make inferences about what those observations mean.

Others (Table 20.2)

- Saying scientific knowledge is empirically based means that scientific knowledge is based on or derived from observations of the natural world. This does not include the supernatural world (e.g., supernatural explanations). Understandings about a particular idea will not be accepted by the scientific community unless it is supported by empirical evidence (from observations or experiments).[1]
- "Science is empirical. The development of scientific knowledge involves making observations of nature...However, scientists do not have direct access to most natural phenomena. Observations are always filtered through our perceptual apparatus..."[1]

[1] Lederman et al. 2002

Source: Guiding questions from Clough (Chapter 15)

Example Response A

Everything is science. You can't get through a whole day without solving a problem of sitting there wondering about something; and to me you can do that in every single discipline.

NOS Subdomain: Empirically Based

Example Response C

Science is when you systematically make careful observations about the natural world and collect data.

NOS Subdomain: Empirically Based

Example Response B

Science can be tested with experiments and making observations but other subjects, like religion, are based on faith.

NOS Subdomain: Empirically Based

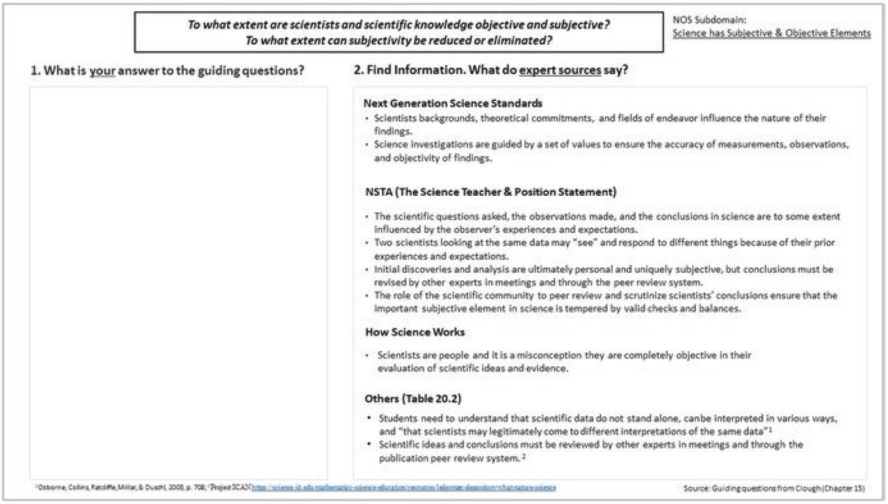
Example Response D

Science is something straightforward and isn't a field of study that allows a lot of opinions, personal bias, or individual views-it is fact based.

NOS Subdomain: Empirically Based

[A] Akerson, V. L., Hanson, D. L, & Cullen, T.A. (2007). The influence of guided inquiry and explicit instruction on K-6 teachers' views of nature of science. *Journal of Science Teacher Education, 18*, 751-772. [B,C] Teacher response from authors' research. [D] Lederman, et al., 2002.

Fig. 20.5 Scientific knowledge is empirically based



To what extent are scientists and scientific knowledge objective and subjective?
To what extent can subjectivity be reduced or eliminated?

NOS Subdomain:
Science has Subjective & Objective Elements

1. What is your answer to the guiding questions?

2. Find Information. What do expert sources say?

Next Generation Science Standards

- Scientists backgrounds, theoretical commitments, and fields of endeavor influence the nature of their findings.
- Science investigations are guided by a set of values to ensure the accuracy of measurements, observations, and objectivity of findings.

NSTA (The Science Teacher & Position Statement)

- The scientific questions asked, the observations made, and the conclusions in science are to some extent influenced by the observer's experiences and expectations.
- Two scientists looking at the same data may "see" and respond to different things because of their prior experiences and expectations.
- Initial discoveries and analysis are ultimately personal and uniquely subjective, but conclusions must be revised by other experts in meetings and through the peer review system.
- The role of the scientific community to peer review and scrutinize scientists' conclusions ensure that the important subjective element in science is tempered by valid checks and balances.

How Science Works

- Scientists are people and it is a misconception they are completely objective in their evaluation of scientific ideas and evidence.

Others (Table 20.2)

- Students need to understand that scientific data do not stand alone, canbe interpreted in various ways, and "that scientists may legitimately come to different interpretations of the same data"[1]
- Scientific ideas and conclusions must be reviewed by other experts in meetings and through the publication peer review system.[2]

[1] Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003, p. 708; [2] Project ICAN

Source: Guiding questions from Clough (Chapter 15)

Example Response A

Scientists are human. They learn and think differently, just like all people do. They interpret the same data sets differently because of the way they learn and think and because of their prior knowledge.

NOS Subdomain: Subjective

Example Response C

Different scientists look at the same topic in different lights drawing from their own theories, backgrounds, and research. While they have the same data, these factors lead them in different directions and approaches to the topic.

NOS Subdomain: Subjective

Example Response B

Scientists are not subjective but very objective because they have a set of procedures they use to solve their problems. Artists are more subjective, putting themselves into their work.

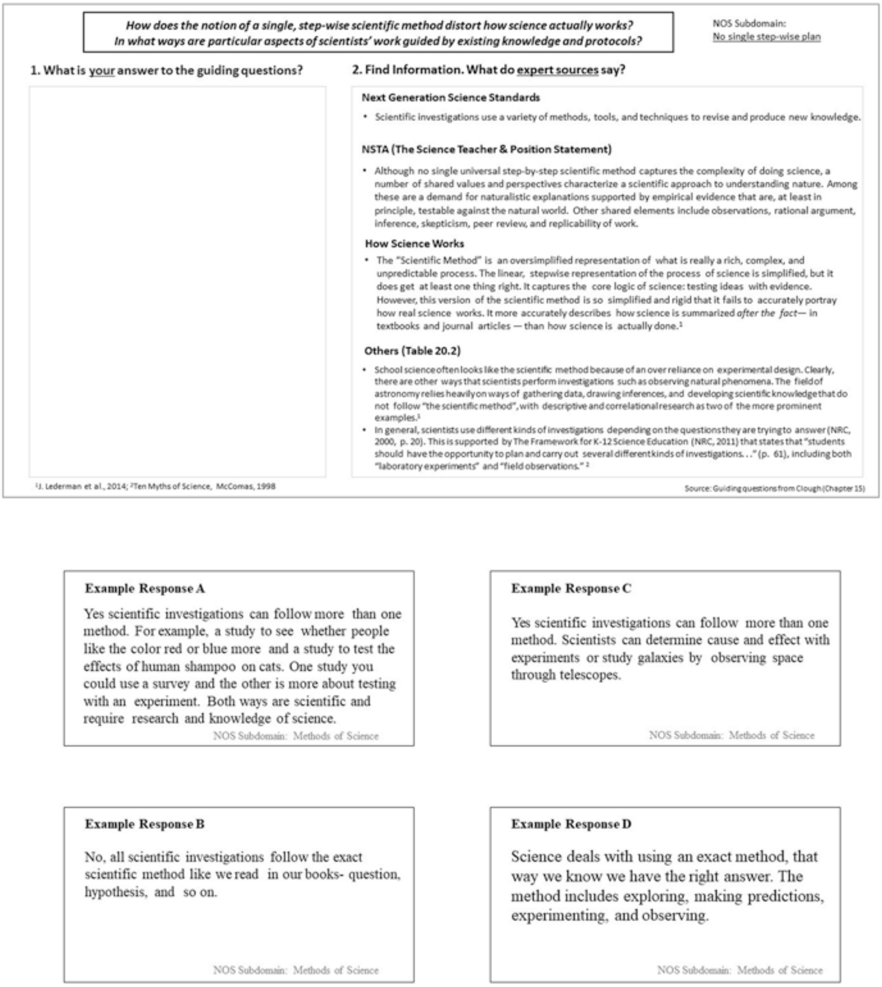
NOS Subdomain: Subjective

Example Response D

Scientists aim to be as objective as possible, as bias negatively impacts science and they are trying to prove things. Yet theories give scientists a framework for which they can interpret data. This is very important to be aware of and know that it impacts interpretation of data.

NOS Subdomain: Subjective

Fig. 20.6 Scientific knowledge has a subjective element



How does the notion of a single, step-wise scientific method distort how science actually works?
In what ways are particular aspects of scientists' work guided by existing knowledge and protocols?

NOS Subdomain:
No single step-wise plan

1. What is your answer to the guiding questions?

2. Find Information. What do expert sources say?

Next Generation Science Standards

- Scientific investigations use a variety of methods, tools, and techniques to revise and produce new knowledge.

NSTA (The Science Teacher & Position Statement)

- Although no single universal step-by-step scientific method captures the complexity of doing science, a number of shared values and perspectives characterize a scientific approach to understanding nature. Among these are a demand for naturalistic explanations supported by empirical evidence that are, at least in principle, testable against the natural world. Other shared elements include observations, rational argument, inference, skepticism, peer review, and replicability of work.

How Science Works

- The "Scientific Method" is an oversimplified representation of what is really a rich, complex, and unpredictable process. The linear, stepwise representation of the process of science is simplified, but it does get at least one thing right. It captures the core logic of science: testing ideas with evidence. However, this version of the scientific method is so simplified and rigid that it fails to accurately portray how real science works. It more accurately describes how science is summarized *after the fact*— in textbooks and journal articles — than how science is actually done.[1]

Others (Table 20.2)

- School science often looks like the scientific method because of an over reliance on experimental design. Clearly, there are other ways that scientists perform investigations such as observing natural phenomena. The field of astronomy relies heavily on ways of gathering data, drawing inferences, and developing scientific knowledge that do not follow "the scientific method", with descriptive and correlational research as two of the more prominent examples.[1]
- In general, scientists use different kinds of investigations depending on the questions they are trying to answer (NRC, 2000, p. 20). This is supported by The Framework for K-12 Science Education (NRC, 2011) that states that "students should have the opportunity to plan and carry out several different kinds of investigations. . ." (p. 61), including both "laboratory experiments" and "field observations." [2]

[1]J. Lederman et al., 2014; [2]Ten Myths of Science, McComas, 1998

Source: Guiding questions from Clough (Chapter 15)

Example Response A

Yes scientific investigations can follow more than one method. For example, a study to see whether people like the color red or blue more and a study to test the effects of human shampoo on cats. One study you could use a survey and the other is more about testing with an experiment. Both ways are scientific and require research and knowledge of science.

NOS Subdomain: Methods of Science

Example Response C

Yes scientific investigations can follow more than one method. Scientists can determine cause and effect with experiments or study galaxies by observing space through telescopes.

NOS Subdomain: Methods of Science

Example Response B

No, all scientific investigations follow the exact scientific method like we read in our books- question, hypothesis, and so on.

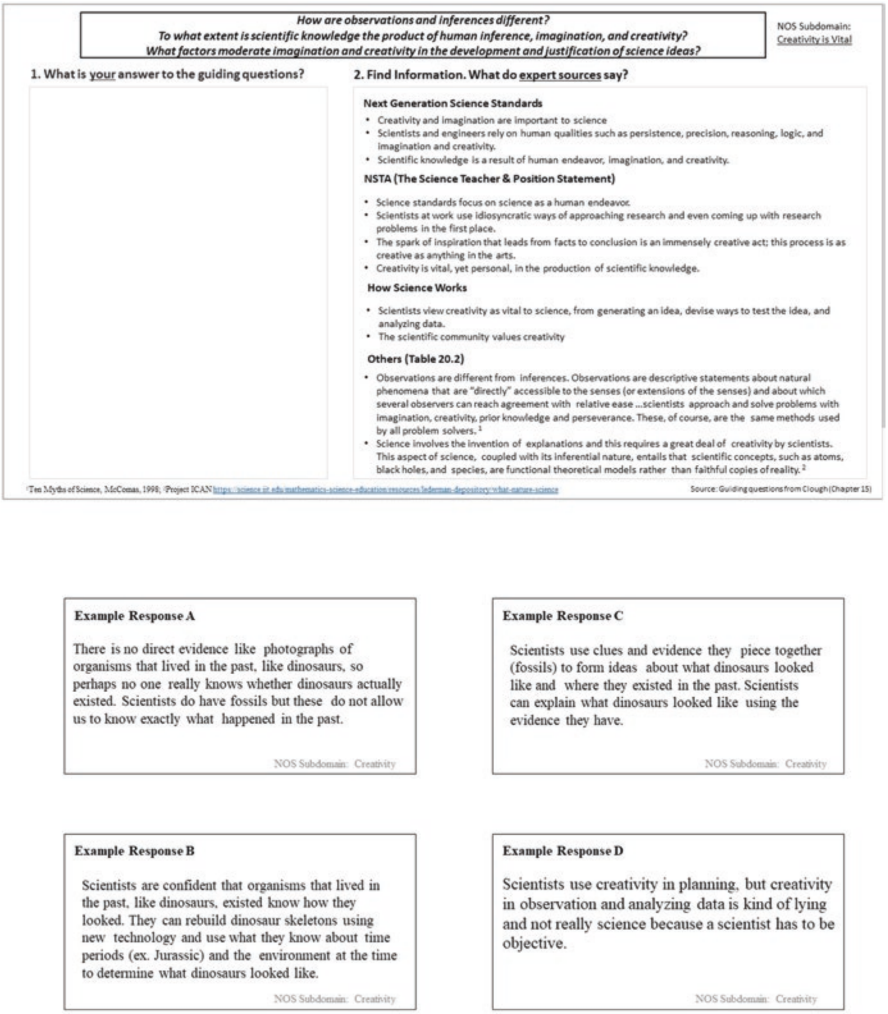
NOS Subdomain: Methods of Science

Example Response D

Science deals with using an exact method, that way we know we have the right answer. The method includes exploring, making predictions, experimenting, and observing.

NOS Subdomain: Methods of Science

Fig. 20.7 Science shares methods but there is no, single, step-wise plan



How are observations and inferences different?
To what extent is scientific knowledge the product of human inference, imagination, and creativity?
What factors moderate imagination and creativity in the development and justification of science ideas?

NOS Subdomain:
Creativity is Vital

1. What is your answer to the guiding questions?

2. Find Information. What do expert sources say?

Next Generation Science Standards

- Creativity and imagination are important to science
- Scientists and engineers rely on human qualities such as persistence, precision, reasoning, logic, and imagination and creativity.
- Scientific knowledge is a result of human endeavor, imagination, and creativity.

NSTA (The Science Teacher & Position Statement)

- Science standards focus on science as a human endeavor.
- Scientists at work use idiosyncratic ways of approaching research and even coming up with research problems in the first place.
- The spark of inspiration that leads from facts to conclusion is an immensely creative act; this process is as creative as anything in the arts.
- Creativity is vital, yet personal, in the production of scientific knowledge.

How Science Works

- Scientists view creativity as vital to science, from generating an idea, devise ways to test the idea, and analyzing data.
- The scientific community values creativity

Others (Table 20.2)

- Observations are different from inferences. Observations are descriptive statements about natural phenomena that are "directly" accessible to the senses (or extensions of the senses) and about which several observers can reach agreement with relative ease ...scientists approach and solve problems with imagination, creativity, prior knowledge and perseverance. These, of course, are the same methods used by all problem solvers.[1]
- Science involves the invention of explanations and this requires a great deal of creativity by scientists. This aspect of science, coupled with its inferential nature, entails that scientific concepts, such as atoms, black holes, and species, are functional theoretical models rather than faithful copies of reality.[2]

[1] Ten Myths of Science, McComas, 1998; [2] Project ICAN https://science.iit.edu/mathematics-science-education/resources/lederman-depository/what-nature-science

Source: Guiding questions from Clough (Chapter 15)

Example Response A

There is no direct evidence like photographs of organisms that lived in the past, like dinosaurs, so perhaps no one really knows whether dinosaurs actually existed. Scientists do have fossils but these do not allow us to know exactly what happened in the past.

NOS Subdomain: Creativity

Example Response C

Scientists use clues and evidence they piece together (fossils) to form ideas about what dinosaurs looked like and where they existed in the past. Scientists can explain what dinosaurs looked like using the evidence they have.

NOS Subdomain: Creativity

Example Response B

Scientists are confident that organisms that lived in the past, like dinosaurs, existed know how they looked. They can rebuild dinosaur skeletons using new technology and use what they know about time periods (ex. Jurassic) and the environment at the time to determine what dinosaurs looked like.

NOS Subdomain: Creativity

Example Response D

Scientists use creativity in planning, but creativity in observation and analyzing data is kind of lying and not really science because a scientist has to be objective.

NOS Subdomain: Creativity

Fig. 20.8 Scientific knowledge is a product of human creativity and inference

References

Abd-El-Khalick, F., & Lederman, N. (2000). Improving science teachers' conceptions of nature of science: A critical review of the literature. *International Journal of Science Education, 22*, 665–701.

Abd-El-Khalick, F., & Akerson, V. (2004). Learning as conceptual change: Factors mediating the development of preservice elementary teachers' views of nature of science. *Science Teacher Education, 88*, 786–810.

Abd-El-Khalick, F., & Akerson, V. L. (2009). The influence of metacognitive training on preservice elementary teachers' conceptions of nature of science. *International Journal of Science Education, 31*, 2161–2184.

Akerson, V. L., Hanson, D. L., & Cullen, T. A. (2007). The influence of guided inquiry and explicit instruction on K-6 teachers' views of nature of science. *Journal of Science Teacher Education, 18*, 751–772.

Akerson, V., & Hanuscin, D. (2007). Teaching nature of science through inquiry: Results of a 3-year professional development program. *Journal of Research in Science Teaching, 44*, 653–680.

Akerson, V., Cullen, T., & Hanson, D. (2009). Fostering a community of practice through a professional development program to improve elementary teachers' views of nature of science and teaching practice. *Journal of Research in Science Teaching, 46*, 1090–1113.

Akerson, V. L., Morrison, J. A., & McDuffie, A. R. (2006). One course is not enough: Preservice elementary teachers' retention of improved views of nature of science. *Journal of Research in Science Teaching, 43*, 194–213.

American Association for the Advancement of Science [AAAS]. (1993). *Benchmarks for science literacy*. New York: Oxford University Press.

Ausubel, D. P. (1968). *Educational psychology: A cognitive view*. New York: Holt, Rinehart and Winston Inc.

Burton, E. (2013). Student work products as a teaching tool for nature of science pedagogical knowledge: A professional development project with in-service secondary science teachers. *Teaching and Teacher Education, 29*, 156–166.

Clough, M. P. (2006). Learners' responses to the demands of conceptual change: Considerations for effective nature of science instruction. *Science Education, 15*, 463–494.

Clough, M. P. (2007). Teaching the nature of science to secondary and post-secondary students: Questions rather than tenets. *The Pantaneto Forum*, 25, retrieved from http://www.pantaneto.co.uk/issue25/clough.htm.

Cobern, W., & Loving, C. (1998). The card exchange: Introducing the philosophy of science. In W. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 73–82). Dorecht: Kluwer Academic Publishers.

Dewey, J. (1910). *How we think*. Boston: D. C. Heath & Co.

Lederman, N., & Abd-El-Khalick, F. (1998). Avoiding de-natured science: Activities that promote understandings of the nature of science. In W. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 83–126). Dordrecht/Boston: Kluwer Academic Publishers.

Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., & Schwartz, R. S. (2002). Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching, 39*, 497–521.

Lederman, N. G., & Lederman, J. S. (2014). Research on teaching and learning of nature of science. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of research on science education* (Vol. ii, pp. 600–620). New York: Routledge.

Kampourakis, K. (2016). The "general aspects" conceptualization as a pragmatic and effective means to introducing students to nature of science. *Journal of Research in Science Teaching, 53*(5), 667–682.

Matkins, J. J., Bell, R., Irving, K., & McNall, R. (2002). Impacts of contextual and explicit instruction on preservice elementary science teachers' understandings of the nature of science. In Proceedings of the Annual International Conference of the Association for the Education of Teachers in Science, Charlotte, NC. January 2002.

McComas, W., & Olson, J. (1998). *The nature of science in science education: Rationales and strategies.* Dordrecht: Kluwer.

McComas, W. (2004). Keys to teaching the nature of science. *The Science Teacher, 71*(9), 24–27.

Mesci, G., & Schwartz, R. (2016). Changing preservice science teachers' views of nature of science: Why some conceptions may be more easily altered than others. *Research in Science Education, 47*(2), 329–351. https://doi.org/10.1007/s11165-015-9503-9.

Morrison, J., Raab, F., & Ingram, D. (2009). Factors influencing elementary and secondary teachers' views on the nature of science. *Journal of Research in Science Teaching, 46*, 384–403.

Mulvey, B., & Bell, R. (2016). Making learning last: Teachers' long-term retention of improved nature of science conceptions and instructional rationales. *International Journal of Science Education, 39*, 1–24.

National Research Council [NRC]. (1996). *National science education standards*. Washington, DC: National Academy Press.

National Research Council [NRC]. (2011). A framework for K-12 science education: Practices, crosscutting concepts. In *And core ideas*. Washington, DC: National Academy Press.

National Academy Press. (1998). *Teaching about evolution and the nature of science*. Washington DC: The National Academies Press.

NSTA Position Statement. (2000). http://www.nsta.org/about/positions/natureofscience.aspx

Osborne, J., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. (2003). What "ideas –about-science" should be taught in school science? A Delphi study of the expert community. *Journal of Research in Science Teaching, 40*, 692–720.

Ozgelen, S., Hanuscin, D. L., & Yilmaz-Tuzun, O. (2013). Preservice elementary science teachers' connections among aspects of NOS: Toward a consistent, overarching framework. *Journal of Science Teacher Education, 24*, 907–927.

Parrish, J. C. (2017). *K-12 teacher professional growth for nature of science and scientific inquiry: promoting reflection through exemplars*. Retrieved from ProQuest Dissertations and Theses database (UMI No. 10289077).

Project ICAN: Inquiry, context, and nature of science. *2006 Annual Report*.

Chapter 21
Practical Learning Resources and Teacher Education Strategies for understanding Nature of Science

Sibel Erduran, Ebru Kaya, Alison Cullinane, Onur Imren, and Sila Kaya

21.1 Introduction

The objective of this chapter is to present some practical resources and strategies for teaching nature of science (NOS) to secondary students and to teachers in in-service training settings. Our work is based on a framework that characterizes NOS as a cognitive-epistemic and social-institutional system (Erduran and Dagher 2014a) and as such, it is consistent with the suggested nine subdomains of NOS for the inclusion of this topic in school science that frames this book. In the following sections, we will discuss our orientation to NOS, including how it relates to these subdomains and present some examples of lesson activities. We will subsequently turn to a discussion of how NOS can be incorporated into science teacher education.

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_21

21.2 Framework on Nature of Science

There are various accounts of the NOS as illustrated in this book. In this chapter, we use the definition of nature of NOS based on the "Family Resemblance Approach" as developed by Erduran and Dagher (2014a). The family resemblance concept originated in Wittgenstein's work and it was applied to the characterization of NOS by Irzik and Nola (2014) through the Family Resemblance Approach (FRA). The idea is that different sciences are grouped together as 'science' because they share a set of characteristics. For example, biology, chemistry and physics are considered science because they share certain aims and values about reliable knowledge. In this sense, they are like a 'family'. They resemble each other because they share certain characteristics but at the same time, they have different features just as members of a family might have. At the same time, different disciplines have different features. For example, even if evidence may be an important feature of all sciences, it will have a different 'flavor' in different sciences. In astronomy the evidence is inherently historical that provides evidence of indirect and past phenomena, whereas in a chemistry experiment, certain variables (e.g. temperature) can be manipulated to produce particular outcomes (e.g. pressure) at this point in time. Overall, the FRA categories are cognitive-epistemic (e.g. aims and values, scientific knowledge) and social-institutional (e.g. social values, financial systems) in nature. Further discussion about the recent developments in the use of FRA in science education is available in Erduran, MacDonald and Dagher (2019). Furthermore, there is a new book on the applications of FRA in chemistry teacher education (Erduran and Kaya, 2019).

Erduran and Dagher (2014a) produced a visual tool to summarize the key ideas involved in FRA (See Fig. 21.1). This figure captures an image of science as a holistic, dynamic and comprehensive system. It is a visual representation showing how the cognitive, epistemic and social-institutional components of science coexist and interact. The cognitive aspects are about the thinking and reasoning processes and strategies that scientists use (e.g. logical reasoning). The epistemic aspects relate to the types of scientific knowledge and how scientific knowledge is produced (e.g. theories, models and laws). The social-institutional aspects highlight the social processes that underpin science as an enterprise (e.g. social institutions where science is done, such as universities, industry and research centers). Altogether, these aspects contribute to what makes science 'science' and how science works at different levels from the mind to the social institutions. Table 21.1 provides the definitions of the categories represented in the FRA wheel.

When we consider Fig. 21.1 and Table 21.1 in relation to the subdomains that are discussed in the opening chapters of this book, we see some overlap. "Special nature of scientific knowledge" is equivalent to the "knowledge" category. "Tools and products of science" captures similar ideas as "practices" and "methods". "Human elements in science" may be unpacked more specifically in the range of outer layer categories in the FRA wheel, including social values and social certification and dissemination. The idea of interaction between the various components of NOS is evident in both representations. Therefore, the representation of concentric circles offered by McComas earlier in this book interacting and intersecting with each other is similarly represented as a set of 'permeable' borders where ideas the cate-

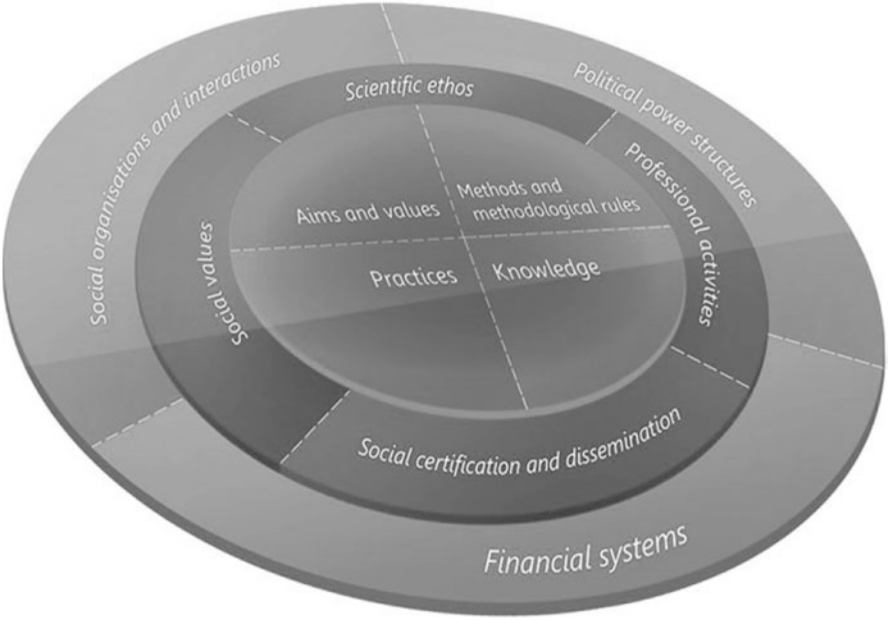


Fig. 21.1 FRA wheel. (From Erduran and Dagher 2014a, p.28)

Table 21.1 Definitions of FRA Categories illustrated in the FRA Wheel in Fig. 21.1

Category	Description
Aims and values	The key cognitive and epistemic objectives of science, such as accuracy and objectivity
Methods	The manipulative as well as nonmanipulative techniques that underpin scientific investigations
Practices	The set of epistemic and cognitive practices that lead to scientific knowledge through social certification
Knowledge	Theories, laws and explanations that underpin the outcomes of the scientific inquiry
Social certification and dissemination	The social mechanisms through which scientists review, evaluate and validate scientific knowledge, for instance through peer review systems of journals
Scientific ethos	The norms that scientists employ in their work as well as in interaction with colleagues
Social values	Values such as freedom, respect for the environment, and social utility
Professional activities	How scientists engage in professional settings, such as attending conferences and doing publication reviews;
Social organizations and interactions	How science is arranged in institutional settings, such as universities and research institutes;
Financial systems	The underlying financial dimensions of science, including the funding mechanisms;
Political power structures	The dynamics of power that exist between scientists and within science cultures

gories are interacting in Erduran and Dagher's (2014a) account. Although Erduran and Dagher's account is similar to McComas' account, one primary difference is the number of categories involved. The former is based on a set of 11 categories, whereas the latter has 3 categories (although McComas' version also has 9 statements associated with each of the 3 main categories). Furthermore, Erduran and Dagher's (2014a) account uses visual tools in order to summarise ideas about NOS. Visualisation can facilitate teaching and learning of abstract concepts such as NOS (Erduran and Kaya, 2018). Here we have used Erduran and Dagher's FRA Wheel and the subset of visual images embedded in it to guide the design of practical lesson resources, as well as a teacher education intervention (Kaya et al., 2019). We review examples of this work to illustrate how the theoretical tools developed by Erduran and Dagher (2014a) have been transformed for practical use.

21.3 Designing Learning Resources

In this section, we review several activities produced in line with each aspect of NOS as characterized in the FRA Wheel (Erduran and Dagher 2014a). In the description of each activity, we will provide the activity itself as well as a discussion of how the activity addresses the category being covered. Erduran and Dagher (2014a) produced a set of visual tools related to each category, which have been used to guide the production of the practical resources. Hence, each section will also illustrate these visual tools and how they can frame lesson activities. The activities for "Aims and Values", "Social-Institutional Aspects", "Practices" and "Methods" have been developed as part of a published resource called "Science Scope" published in Ireland. Science Scope is a science supplement for the middle school science classroom (students aged 12–15 years of age) published by the Irish Independent newspaper and available for distribution. (Please note that the title of this supplement is like that in an NSTA publication. Therefore, we would like to draw the reader's attention to the fact that the resources discussed in this chapter are not in any way related to those in NSTA resources.) Nine supplements are produced in a year and they are disseminated to schools registered with the newspaper. The activities will show how they support each FRA category. These activities serve multiple purposes and could serve as summative assessment or, more favorably, formative group work and discussion in the science classroom and also offer ideas for teachers to extend for future project work. We sought to find issues that would present real life implications both nationally and internationally that could satisfy curriculum topics, as socioscientific issues could be a novel approach to capturing students' imagination and interest. We give examples of these issues, such as conservation of species, an issue that may have social as well as ecological significance. The example topics are relevant to the contemporary developments in curriculum reform, for example, in Ireland (Erduran and Dagher 2014b), Turkey (Kaya and Erduran, 2016) and Taiwan (Yeh et al. 2019). The "Scientific Knowledge" category example and discussions regarding teacher education are derived from a funded project based at Bogazici University, Turkey (Erduran and Kaya, 2018; Kaya et al. 2019).

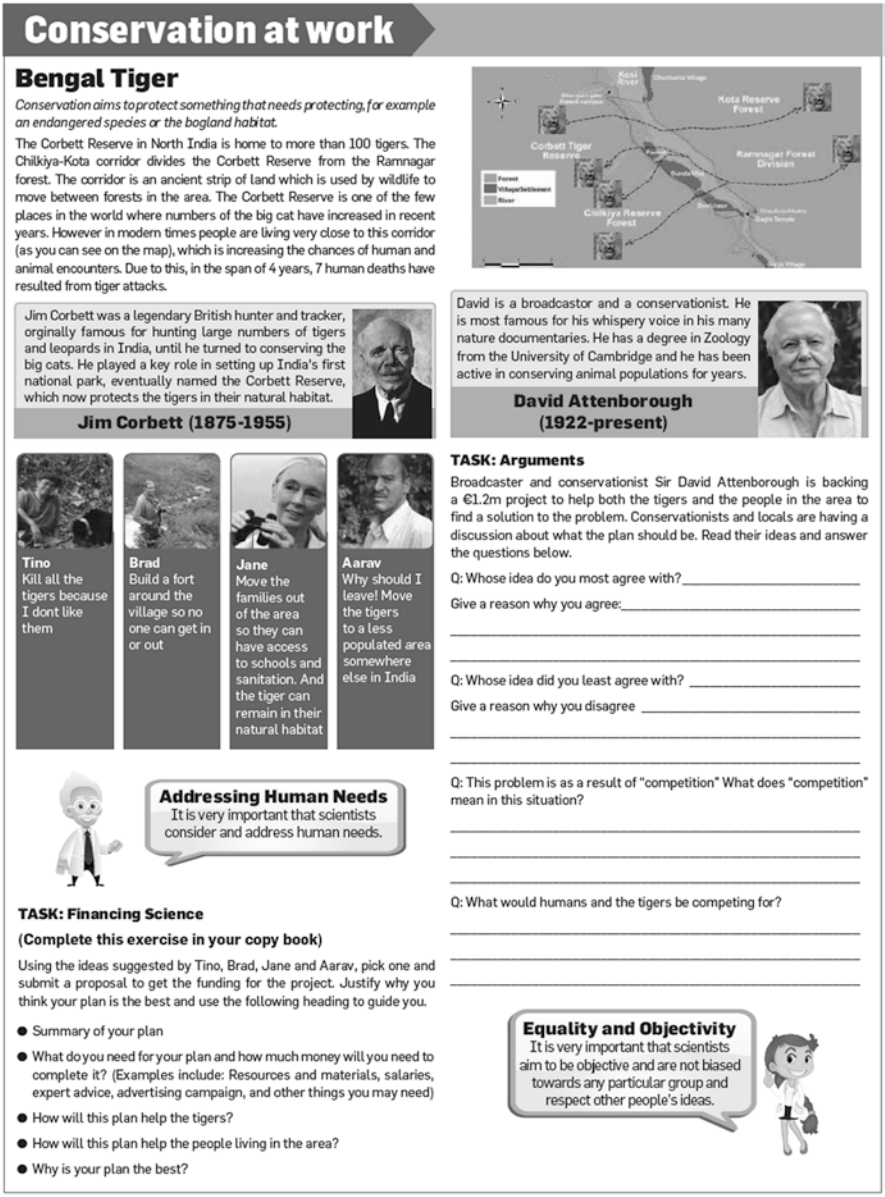
21.3.1 Aims and Values of Science

Figure 21.2 illustrates an activity that was published by Irish Independent Newspaper. The aspects of NOS that the activity incorporates are highlighted in Table 21.2. The activity tells the story of a recent news event where the conservation of tigers in the Corbett Reserve, North India was impacting local villages. The number of tigers has risen because of conservation efforts and encounters with humans and tigers have increased. Consequently, this rise resulted in many human deaths. At the same time, broadcaster and conservationist, Sir David Attenborough, has been involved in a large funded project to help protect the tigers and the people involved. The activity is designed to support the category of "*Aims and values"*. It also satisfies the curriculum topic of ecology, particularly the subtopic of conservation. It captures several other categories from the wheel such as "Practices", "Social Values", "Professional Activities" and "Financial Systems", which will be highlighted in the discussion. This activity draws on educational applications presented in Table 21.2 that shows the applications of epistemic–cognitive and social aims and values of science in science education.

This activity touches on a number of these aims and values, such as objectivity (i.e. seeking neutrality and avoiding bias), empirical adequacy (i.e. basing claims on sufficient, relevant and plausible data), critical examination (i.e. giving a reason to justify claims), addressing human needs (i.e. consider and respecting human needs) and taking the challenges seriously (i.e. taking opposition to own ideas seriously). In other words, examples of aims and values are transformed into corresponding terminology to be accessible from the students' point of view.

The main task in the activity is an exercise on argumentation (e.g. Toulmin, 1958), where students are given four statements by fictional characters developed to tell the story. Despite the underlying framing of the activity with "Aims and Values" category, incorporating argumentation into the activity extends it to the "Practices" category. The NCR (2012) highlight arguments as one of its eight essential practices (*engaging in argument from evidence p.42)*. It is seen as a pedagogical strategy that supports science writing and is an important discourse activity and process in science learning and thinking. Several research publications point to the importance of incorporating argumentation in the science classroom (Erduran 2019; Erduran et al. 2015, Erduran and Jimenez-Aleixandre 2007). Argumentation is defined as the process of coordinating evidence and theory to support or refute an explanatory conclusion, model or prediction has emerged as a significant educational goal. The activity promotes argumentation by engaging students in discussions about the aims and values that scientists propose in making decisions on socioscientific issues.

Each argument is described and justified why it is included and how it is framed by the "Aims and Values" category. The first fictional character is depicted by an ecologist, Tino, who is expressing to kill the tigers because he doesn't like them. His statement is used to highlight that scientists cannot be subjective to their own "likes" or "dislikes". This draws on Table 21.1 on objectivity, to seek neutrality and avoid bias. The second ecologist is depicted by Brad whose statement is used as a distractor to address empirical adequacy, such that scientists base their decisions on sufficient,



Conservation at work

Bengal Tiger

Conservation aims to protect something that needs protecting, for example an endangered species or the bogland habitat.

The Corbett Reserve in North India is home to more than 100 tigers. The Chilkiya-Kota corridor divides the Corbett Reserve from the Ramnagar forest. The corridor is an ancient strip of land which is used by wildlife to move between forests in the area. The Corbett Reserve is one of the few places in the world where numbers of the big cat have increased in recent years. However in modern times people are living very close to this corridor (as you can see on the map), which is increasing the chances of human and animal encounters. Due to this, in the span of 4 years, 7 human deaths have resulted from tiger attacks.

Jim Corbett was a legendary British hunter and tracker, orginally famous for hunting large numbers of tigers and leopards in India, until he turned to conserving the big cats. He played a key role in setting up India's first national park, eventually named the Corbett Reserve, which now protects the tigers in their natural habitat.

Jim Corbett (1875-1955)

Tino
Kill all the tigers because I dont like them

Brad
Build a fort around the village so no one can get in or out

Jane
Move the families out of the area so they can have access to schools and sanitation. And the tiger can remain in their natural habitat

Aarav
Why should I leave! Move the tigers to a less populated area somewhere else in India

Addressing Human Needs
It is very important that scientists consider and address human needs.

TASK: Financing Science

(Complete this exercise in your copy book)

Using the ideas suggested by Tino, Brad, Jane and Aarav, pick one and submit a proposal to get the funding for the project. Justify why you think your plan is the best and use the following heading to guide you.

- Summary of your plan
- What do you need for your plan and how much money will you need to complete it? (Examples include: Resources and materials, salaries, expert advice, advertising campaign, and other things you may need)
- How will this plan help the tigers?
- How will this plan help the people living in the area?
- Why is your plan the best?

David is a broadcastor and a conservationist. He is most famous for his whispery voice in his many nature documentaries. He has a degree in Zoology from the University of Cambridge and he has been active in conserving animal populations for years.

David Attenborough (1922-present)

TASK: Arguments

Broadcaster and conservationist Sir David Attenborough is backing a €1.2m project to help both the tigers and the people in the area to find a solution to the problem. Conservationists and locals are having a discussion about what the plan should be. Read their ideas and answer the questions below.

Q: Whose idea do you most agree with?____________________

Give a reason why you agree:__________________________

Q: Whose idea did you least agree with? ____________________

Give a reason why you disagree ________________________

Q: This problem is as a result of "competition" What does "competition" mean in this situation?

Q: What would humans and the tigers be competing for?

Equality and Objectivity
It is very important that scientists aim to be objective and are not biased towards any particular group and respect other people's ideas.

Fig. 21.2 Exploring the aims and values of science: The Bengal Tiger cctivity. (Irish Independent 2015)

relevant and plausible claims. Building a fort around a village, where no-one can get in or out, is not a logical solution and would be a short-term solution not a long-term one. The third character is Jane, depicted by the image of Dame Jane Goodall, the famous anthropologist. The news story allude to a systematic approach to solving a

Table 21.2 Application of cognitive-epistemic and social aims and values of science in science education. (From Erduran and Dagher 2014a, p.52)

Aspect	Aim/value	Educational application
Epistemic-cognitive	Objectivity	Seeking neutrality and avoiding bias
	Novelty	Searching for new explanations
	Accuracy	Ensuring that explanations are accurate
	Empirical adequacy	Basing claims on sufficient, relevant and plausible data
	Critical examination	Giving reasons to justify claims
	Addressing anomalies and counter instances	Recognizing opposite ideas and responding to objections
	Taking challenges seriously	Taking opposition to own ideas seriously
Social	Addressing human needs	Considering and respecting human needs
	Decentralizing power	Making sure nobody controls ideas to favor particular group biases
	Honesty	Being honest and acting honestly in all aspects of scientific activities
	Equality of intellectual authority	Respecting all ideas as long as they are evidence-based regardless of whose ideas they are

problem, and so this aspect is reflected in Jane's statement. The solution has the greatest impact on the lives of both the tigers and the humans. It highlights how scientists aim to seek neutrality and avoid bias toward any particular group. The final character depicts Aarav, a local villager, whose statement shows the need to engage the public in decision-making in science. The use of this character gets at how the aims and values of scientists need to include values such as respect for people. The decisions affect the local community. Therefore, scientists must show that they are not being biased towards any particular group.

21.3.2 Social-Institutional System

Erduran and Dagher (2014a) refer to the 7 categories in the two outer concentric circles of the FRA Wheel as the "Social-Institutional System". Collectively, these categories are about the social and institutional aspects of science. In the Bengal Tiger activity (Fig. 21.2), the images of the characters involved in the argumentation piece were selected to convey that scientists do not always wear white coats and can conduct valid scientific research outside of a laboratory, essentially humanizing science. The reminder of the question highlights ecological concepts, such as competition, and asks for the definition of competition in the ecological situation. The activity provides information on Jim Corbett and Sir David Attenborough to distinguish between some historical and modern conservationists. The story of Jim Corbett highlights the category "Social Values" which is a subset of "Social-Institutional System". Social values of the scientist can have a significant impact on the direction of modern society. There are implicit inferences of how the aims and values of Jim Corbett changed the direction of tiger ecology in the area. In contrast, the information on Sir David Attenborough provides a picture of a modern-day conservationist and provides insight into the impact famous figures can play in highlighting science in the media.

The final task *"Financing science"* at the bottom of the page touches on another category "Financial Systems", which is part of Erduran and Dagher's (2014a) "Social-Institutional System" category. The theme is used to show that scientists need financial backing to conduct science and need to apply for a grant or bid for the project. Often finances drive what is being researched in science. Science does not just happen with no economic context. Scientific projects need to be funded so that they can be resourced in terms of staff, equipment, materials and dissemination. This activity too provides a platform to show students a view of science that incorporates its economic dimension. It opens the doors a little wider to students to show that the community of scientists requires all sorts of minds that can address different dimensions of science. The activity asks the students to develop a proposal using the statements suggested by the characters Tino, Brad, Jane and Aarav, justifying why they think their plan is the best. It provides structured steps to guide their proposal. Students are asked to give a summary of the plan; what resources and financial support they need (e.g. resources and materials, salaries expert advice, advertising campaign), how the plan will help the tigers; and how the plan will help the people living in the area. The inclusion of economic perspectives in science education ensures that learners of science are equipped with the skills to understand that science has a financial dimension (Erduran and Mugaloglu 2013).

21.3.3 Scientific Practices

Erduran and Dagher (2014a) characterized scientific practices as a set of epistemic, cognitive and social practices that underpin how scientists do science. Scientists engage in particular activities such as classification, experimentation and observation in order to generate data which then get modeled. Modeling enables scientists to explain and predict phenomena. These cognitive and epistemic processes are mediated by social practices, including discussions and representations. Erduran and Dagher produced a visual tool called "Benzene Ring Heuristic" (BRH) to summarize the key concepts related to scientific practices (see Fig. 21.3). The "States of Rugby" activity (see Fig. 21.4) was guided by the BRH. "States of Rugby" is grounded in (1) classification which is part of activities such as experimentation and observation and (2) modeling. Classification can be used as a heuristic in discovery, analysis and theorizing throughout the primary stages of inquiry (Davies 1989). In school science, classification included in the scientific practices has been usually addressed as a tool to organize observations without emphasizing its explanatory/predictive power (Erduran and Dagher 2014a). The rationale for choosing rugby to teach states of matter is that teaching science in an

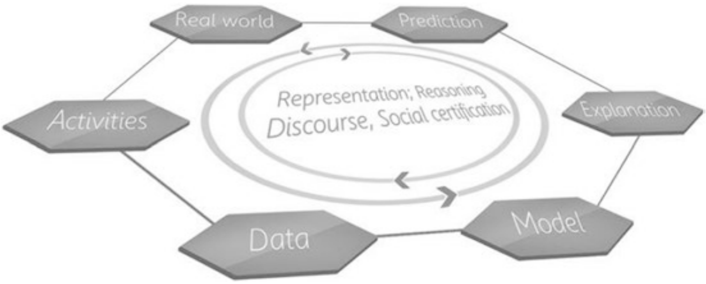
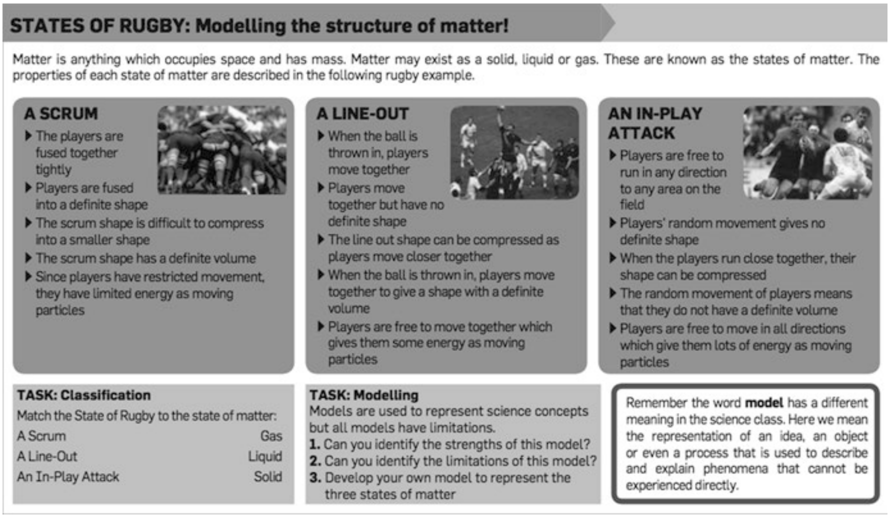


Fig. 21.3 "Benzene Ring Heuristic" of scientific practices. (From Erduran and Dagher 2014a, p. 82)



STATES OF RUGBY: Modelling the structure of matter!

Matter is anything which occupies space and has mass. Matter may exist as a solid, liquid or gas. These are known as the states of matter. The properties of each state of matter are described in the following rugby example.

A SCRUM
- The players are fused together tightly
- Players are fused into a definite shape
- The scrum shape is difficult to compress into a smaller shape
- The scrum shape has a definite volume
- Since players have restricted movement, they have limited energy as moving particles

A LINE-OUT
- When the ball is thrown in, players move together
- Players move together but have no definite shape
- The line out shape can be compressed as players move closer together
- When the ball is thrown in, players move together to give a shape with a definite volume
- Players are free to move together which gives them some energy as moving particles

AN IN-PLAY ATTACK
- Players are free to run in any direction to any area on the field
- Players' random movement gives no definite shape
- When the players run close together, their shape can be compressed
- The random movement of players means that they do not have a definite volume
- Players are free to move in all directions which give them lots of energy as moving particles

TASK: Classification
Match the State of Rugby to the state of matter:
A Scrum Gas
A Line-Out Liquid
An In-Play Attack Solid

TASK: Modelling
Models are used to represent science concepts but all models have limitations.
1. Can you identify the strengths of this model?
2. Can you identify the limitations of this model?
3. Develop your own model to represent the three states of matter

Remember the word **model** has a different meaning in the science class. Here we mean the representation of an idea, an object or even a process that is used to describe and explain phenomena that cannot be experienced directly.

Fig. 21.4 Scientific practices activity: States of Rugby. (Irish Independent 2015)

authentic and enjoyable way is possible when real life examples such as rugby are used. For example, Six Nations Rugby Matches, performed in February 2015, were followed enthusiastically by people all over the world and had also a local impact in Ireland. Due to its local and global impact, the analogy of rugby was chosen to guide the content of the activity.

In Fig. 21.4, note the three boxes. Each box represents one state of matter – solid, liquid and gas – with an analogy to a rugby position –a scrum, a line-out and an in-play attack. Following the descriptions of the rugby positions, in the first task "TASK: Classification", students were asked to match the "States of Rugby" to states of matter. After making students aware of the analogy and gaining an insight on the resemblance between these states, in the second task "TASK: Modeling", three questions were posed to students. Two of those questions are to identify the strengths and weaknesses of the model and one of them is to support students to develop their own model by arguing the example model, “States of Rugby”. Ultimately, in order to make students realize different descriptions of modeling, a small box presenting one of the definitions of the ‘model’ was used. “States of Rugby” shows how high-level theoretical explanations can be simplified and embodied for 11 to 14-year-old students. The activity considers students’ cognitive capacities and is intended to facilitate students’ understanding broadly of how science works, as well as to improve their understanding of scientific practices.

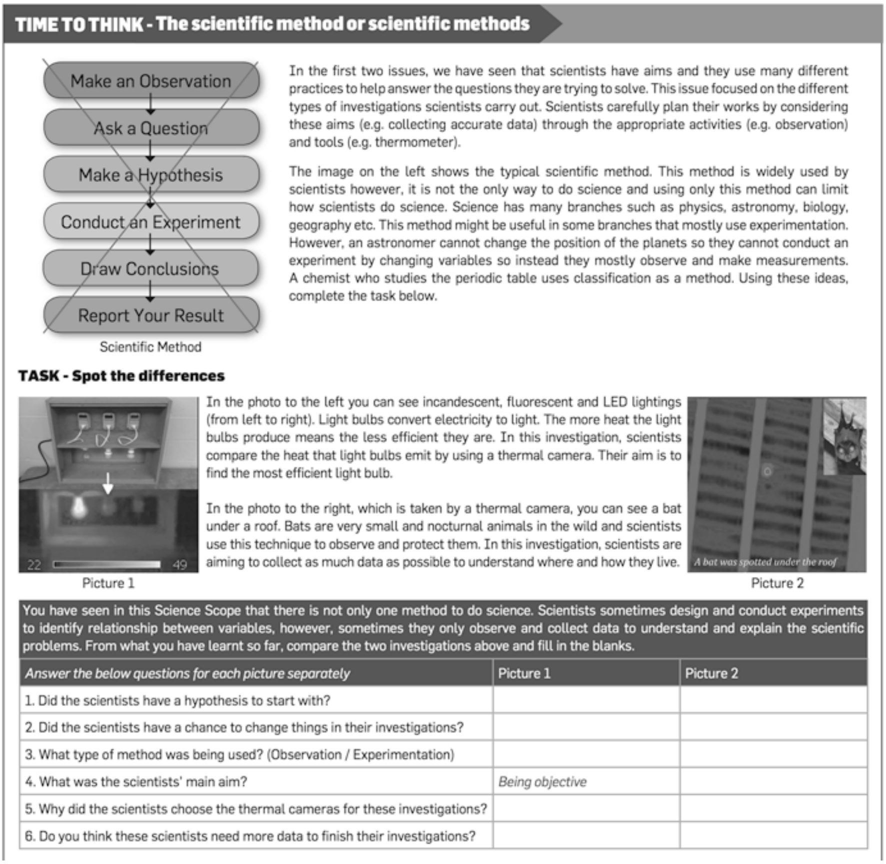
The activity focuses on the explanatory/predictive power of models in the “States of Rugby” model to teach classification of the states of matter. Furthermore, by doing the first task, students can gain insight on classification by presenting a high-level cognitive process in a less complicated way. Within this context, some features of rugby were presented by referring to the properties of states of matter. For example, in “a scrum”, by saying that “the scrum shape cannot be compressed into a smaller shape”, incompressibility of solids was implied. Furthermore, by saying that “the players are fused together tightly”, a hint is given about whether the atoms of a solid are compressible. Based on the use of classification in the first task, students will be able to classify the properties of a matter. By using the components of BRH such as activities, real world and explanation, it is anticipated that students will be able to understand how modeling helps scientists coordinate data to reach explanatory conclusions. Models can also be used to predict phenomena; and represent an idea, an object or even a process to explain complicated or abstract situations. In this activity, although students cannot directly see the atoms, they imagine the rugby players as atoms to support their visualization. Additionally, after exploring that “States of Rugby” is a model, in the second task, students criticize, analyze and evaluate the strengths and weaknesses of this model. The three questions posed in the “TASK: Modelling” section at the end of the activity aim to improve students’ understanding of modeling, and to make them realize that models can also have limitations.

21.3.4 Scientific Methods

The “Scientific Methods” category illustrates the diversity of methods that scientists use (see Table 21.3). Erduran and Dagher (2014a) used a framework based on Brandon’s (1994) work to highlight the various types of scientific methods. Scientists sometimes manipulate variables, sometimes they do not. Sometimes they test hypotheses, sometimes they simply measure parameters. These ideas were incorporated into the activity entitled *“The scientific method or scientific methods?”* which was published in the April 2015 heat and temperature edition of Irish Independent Newspaper’s Science Scope (See Fig. 21.5). The activity targeted the curriculum topic of heat, as well as the category of “Scientific Methods”. The activity starts with a brief introduction to scientific methods. It includes an image of the traditional scientific method with a big X mark on it. The meaning of X mark is

Table 21.3 Types of observational and experimental methods (from Erduran & Dagher, 2014a, p.100)

		Experiment/Observation	
		Manipulate	Non-manipulate
Descriptive/ experimental	**Test hypothesis**	Manipulative hypothesis test	Nonmanipulative hypothesis test
	Measure parameter	Manipulative description or measure	Nonmanipulative description or measure



TIME TO THINK - The scientific method or scientific methods

In the first two issues, we have seen that scientists have aims and they use many different practices to help answer the questions they are trying to solve. This issue focused on the different types of investigations scientists carry out. Scientists carefully plan their works by considering these aims (e.g. collecting accurate data) through the appropriate activities (e.g. observation) and tools (e.g. thermometer).

The image on the left shows the typical scientific method. This method is widely used by scientists however, it is not the only way to do science and using only this method can limit how scientists do science. Science has many branches such as physics, astronomy, biology, geography etc. This method might be useful in some branches that mostly use experimentation. However, an astronomer cannot change the position of the planets so they cannot conduct an experiment by changing variables so instead they mostly observe and make measurements. A chemist who studies the periodic table uses classification as a method. Using these ideas, complete the task below.

TASK - Spot the differences

In the photo to the left you can see incandescent, fluorescent and LED lightings (from left to right). Light bulbs convert electricity to light. The more heat the light bulbs produce means the less efficient they are. In this investigation, scientists compare the heat that light bulbs emit by using a thermal camera. Their aim is to find the most efficient light bulb.

In the photo to the right, which is taken by a thermal camera, you can see a bat under a roof. Bats are very small and nocturnal animals in the wild and scientists use this technique to observe and protect them. In this investigation, scientists are aiming to collect as much data as possible to understand where and how they live.

Picture 1

Picture 2

You have seen in this Science Scope that there is not only one method to do science. Scientists sometimes design and conduct experiments to identify relationship between variables, however, sometimes they only observe and collect data to understand and explain the scientific problems. From what you have learnt so far, compare the two investigations above and fill in the blanks.

Answer the below questions for each picture separately	Picture 1	Picture 2
1. Did the scientists have a hypothesis to start with?		
2. Did the scientists have a chance to change things in their investigations?		
3. What type of method was being used? (Observation / Experimentation)		
4. What was the scientists' main aim?	*Being objective*	
5. Why did the scientists choose the thermal cameras for these investigations?		
6. Do you think these scientists need more data to finish their investigations?		

Fig. 21.5 Scientific methods activity: The scientific method or scientific methods. (Irish Independent 2015)

explained to correct one of misconception in scientific process. As mentioned by many researchers (e.g. McComas 1998; Matthews 2012), the traditional scientific method generates many misconceptions, such as there is only one way to do science, which is a linear and straightforward process, and all scientific works include experiments in a laboratory. The introduction also includes examples of an astronomer investigating plants, and a chemist exploring elements of the periodic table. These examples are intended to show that the traditional method (i.e. hypothesis testing through control of variables in experiments) does not fit on all scientific topics. The introduction part is followed by a task including two different scientific studies related to the theme of diversity of scientific methods. The main aim of this task is to find the differences between the scientific methods chosen for these studies.

In the first fictional study, scientists compare different types of light bulbs to see their electricity consumption and they test the hypothesis that there is a negative relationship between the heat produced by light bulbs and their energy efficiencies. In the second study, scientists use thermal cameras to make observations on bats. They use thermal cameras to observe them because they are very small and nocturnal animals in the wild and it is difficult to observe them with the naked eye. This technique allows researchers to collect more accurate data and helps them to understand bat behavior. This activity includes six questions and each question draws on different educational but mainly scientific methods and methodological rules. There are 4 questions related to scientific methods, one question for aims and values, and scientific practices related to each question. The first and second questions in this task draw on the differences between observational and experimental methods. Erduran and Dagher (2014a) highlight the types of observational and experimental methods in Table 21.3.

The first question in this task is about whether having a hypothesis is necessary before starting a scientific investigation. There are 5 other questions. These questions require simple yes/no answers. However, students should be able to define the hypothesis in the first study, which is about the heat and energy consumption. On the other hand, scientists from the second study have no hypothesis, neither explaining where bats can be found nor how many bats should be there. The second question is about manipulation. By manipulation, we mean the effort made by researchers that changes the variables or the environment of the study. This question also requires yes/no answers. In the first study, scientists are using variables and directly manipulating what they study by choosing different types of light bulbs to investigate. The other study aims to demonstrate how scientists have no influence on bats. They observe the animals in their natural environment without interfering with them and their study does not influence the bats' behavior. These two studies were deliberately chosen as they both used heat (the thermal cameras) in the study, but also used heat in different ways to make observations and claims about what was being investigated. By answering these two questions, note that the first study draws on manipulative hypothesis testing, while the second study falls under nonmanipulative description. The first study would be nonmanipulative hypothesis testing if researchers compare the light bulbs that they use in their daily life without picking any type of light bulb. Likewise the second study would be manipulative description if researchers place the bats in a specific environment and observe them in various conditions.

The aim of the first two questions was to show that there are various scientific methods in science. It is also important to know that there are distinct types of research questions and they require different methods to answer. By asking the fifth question in this task, we highlight that even though the same tools (thermal cameras) are being used in two studies, they serve different purposes because of the nature of their research questions. The first research question requires testing, which is directly related to experimentation, in contrast to second study that requires explanation, which is related to observation. Finally, by asking the last question in this task, we engage the students in thinking about whether choosing one scientific method is enough to answer a research question. As Erduran and Dagher (2014a, p.101) illustrate in Fig. 21.6, evidence from a variety of methods works together in the formulation of scientific explanations.

In this activity, the second study clearly needs additional evidence that might come from various scientific methods, because understanding an animal behavior is complex. On the other hand, using only one method seems appropriate to answer the first research question, which is comparing several types of light bulbs. In summary, the activity promotes the learning of not only the diversity of methods in science but also the nuance in which different scientific problems can be situated as an example of a different method if the research questions are altered. In summary, the activity promotes the learning of not only the diversity of methods in science but also the nuance in which different scientific problems can be situated as an example of a different method if the research questions are altered. In a recent study (Cullinane et al. 2019), we have explored further the nature of scientific methods in high stakes examination papers to find out how examinations might be biasing particular times of scientific methods. The outcomes of the study included the observation that there were relatively more questions dedicated to non-manipulative parameter measurement as compared to manipulative parameter measurement in tests from three examination boards' papers. The relative distribution of marks was not consistent suggesting that more marks were dedicated to manipulative parameter measurement as compared to the number of items covered in the examination. The study highlights the utility of Brandon's (1994) categorization in understanding what is important to teach and indeed to assess in science education.

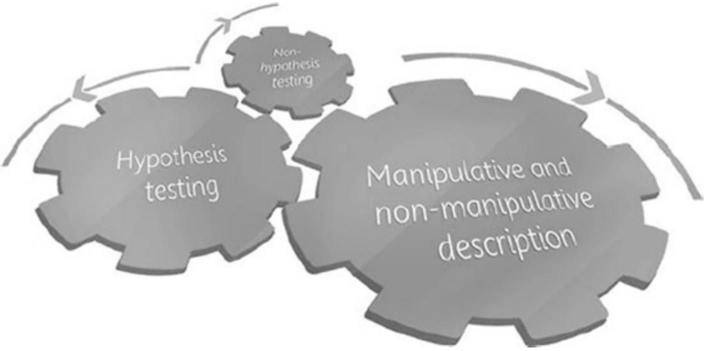


Fig. 21.6 The 'gears' image illustrating how evidence from a variety of methods works synergistically to contribute to explanatory consilience. (From Erduran and Dagher 2014a, p.101)

21.3.5 *Scientific Knowledge*

Although the science curriculum is typically overcrowded with scientific knowledge, meta-perspectives on scientific knowledge tend to be limited. Furthermore, in school science, the connection between various forms of scientific knowledge (i.e. theories, laws and models) and their influence on the scientific explanations is not clear Erduran and Dagher (2014a) developed a heuristic represented in Fig. 21.7 that is intended to illustrate the coordination of theories, laws and models (TLM) working together in contributing to scientific knowledge. Another aspect of the heuristic is that it illustrates growth of scientific knowledge. The boxes in Fig. 21.7 represent the progressive accumulation in theories, laws and models, as new evidence is gathered. The arrows illustrate the process of growth and how TLM contributes to scientific understanding. The entire plane is about a particular framework within which scientists work at a particular point in time. For example, the entire paradigm of the atomic theory would be represented as the overall plane that comprises the atomic theory, models of the atoms and laws, such as periodicity. If new evidence emerges that contradict TLM, the entire plane might be started again in the context of a paradigm shift. Thus, TLM is a meta-tool that highlights the significance of understanding what constitutes scientific knowledge. Further discussion about TLM and its use in teacher education can be found in Erduran and Kaya (2019; 2018).

In the science teacher education project conducted at Bogazici University with preservice science teachers, we developed an activity represented in Fig. 21.8. (Full details of the project can be accessed in a recent book (Erduran and Kaya 2019). The teacher education intervention was part of a funded project whose aim was to infuse various aspects of NOS in science education, including the nature of scientific knowledge. Preservice teachers participated in a series of workshops that

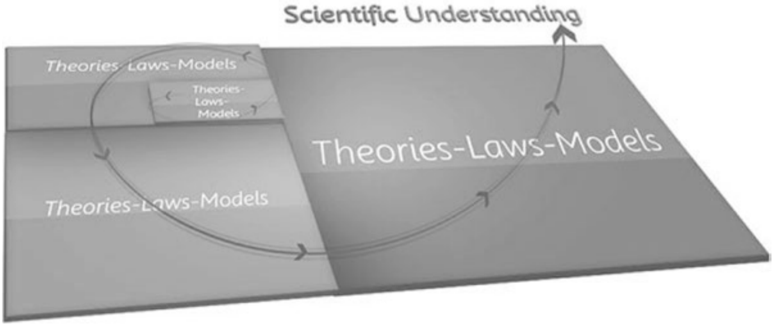


Fig. 21.7 TLM, growth of scientific knowledge and scientific understanding. (From Erduran and Dagher 2014a, p. 115)

Have a look at the following table that summarizes some examples of theories, laws, and models (TLM) in different science domains.

	Biology	**Chemistry**	**Physics**
Theory	Genetic theory	Atomic theory	Thermodynamics
Law	Inheritance law	Periodic law	Laws of thermodynamics
Model	Genes	Atomic model	Heat transfer
TLM explain	Biological traits	Structure of matter	Heat

- *Discuss the examples before moving on to the next steps. What do you notice about the terms?*
- *In your groups, produce a list of 6 other examples of theories, laws, models from any domain of science (i.e. 3 sets of TLM);*
- *In your list include 4 science concepts that are NOT examples of theories, laws and models. The purpose of this set of concepts is to promote discussion about what counts as theories, laws and models and what does not.*
- *In your groups, write down the terms on separate pieces of paper and place the whole set (3 sets of TLM and the 4 unrelated concepts) in an envelope;*
- *Hand over your envelope to the next group. Take a set from the other group!*
- *In your groups, sort out the other group's cards into TLMs! Put the unrelated* concepts separately.
- One person from each group visits the group who received their cards and discusses the categories of TLM.

Fig. 21.8 Scientific knowledge activity used in preservice teacher education (from Erduran and Kaya, 2019, pp. 94–95)

focused on particular themes such as scientific knowledge. In the workshop focusing on scientific knowledge, the preservice science teachers engaged in a task that asked them to produce examples of theories, laws, models from any domain of science. For example, for gas topic, they wrote kinetic energy theory, gas laws and the models representing the particulate nature of gases. Each group then evaluated another group's examples to sort them out, which reinforced understanding of theories, laws and models. In the second part of the activity, the preservice science teachers researched examples of paradigm shifts, where theories, laws and models would now be considered relative to how they change across time. The group then produced a poster to communicate their examples on paradigm shifts.

21.4 Strategies for Including NOS in Science Teacher Education

The preceding discussion about the design of learning resources needs to be complemented by strategies for science teacher education such that these resources can ultimately be taught effectively. In other words, the design of learning resources, we believe, needs to be coupled with innovative strategies to engage teachers in learning to teach NOS. There is plenty of evidence that teaching of NOS is challenging for science teachers (e.g. Akerson et al. 2000). The example resources can be used in teacher education with an eye towards empowering teachers to produce activities of their own. In our teacher education intervention project (e.g. Kaya et al. 2019; Erduran and Kaya 2019), we used numerous active learning strategies, such as group discussions, presentations, posters and microteaching. Fig. 21.9 illustrates an activity on "Scientific Methods" conducted with preservice teachers, where argumentation was used as a strategy. In this activity, there are two opposing claims. Claim 1 takes the position that all science disciplines use the same scientific method, whereas Claim 2 advances the position that each scientific discipline uses a different method. Different reasons and evidence can be appealed to in order to support either claim. For example, the following statement can be used to support Claim 2: *"some sciences such as astronomy do not involve experiments as the scientific method because we cannot manipulate the planets, whereas others, like chemistry, include manipulation of variables, such as pressure and temperature of a gas"*.

During the group discussion that followed, preservice science teachers constructed posters to illustrate their ideas about the task. The analysis of the poster (Fig. 21.10) resulted in the following key observations in their visual representation of scientific methods: (a) the differentiation of a single scientific method versus a diversity of methods in different branches of science, (b) the use of modes of transport (e.g. plane, car, ship) as an analogy to illustrate how different methods serve

Claim 1: All science disciplines use the same stepwise methods. There is one universal scientific method.

Claim 2: All science disciplines do not use the same stepwise methods. Each discipline uses a different method.

- *In your groups, each person will choose either claim 1 or 2 and produce a list of reasons to support this claim. (You may or may not agree with the claim. Focus on producing the reasons, not agreeing or disagreeing with the claim.)*
- *After discussing your claims in your groups, produce a poster to summarize the key ideas for each claim.*

Fig. 21.9 The use of argumentation strategy in "scientific methods" activity (from Erduran and Kaya, 2019, p. 92)

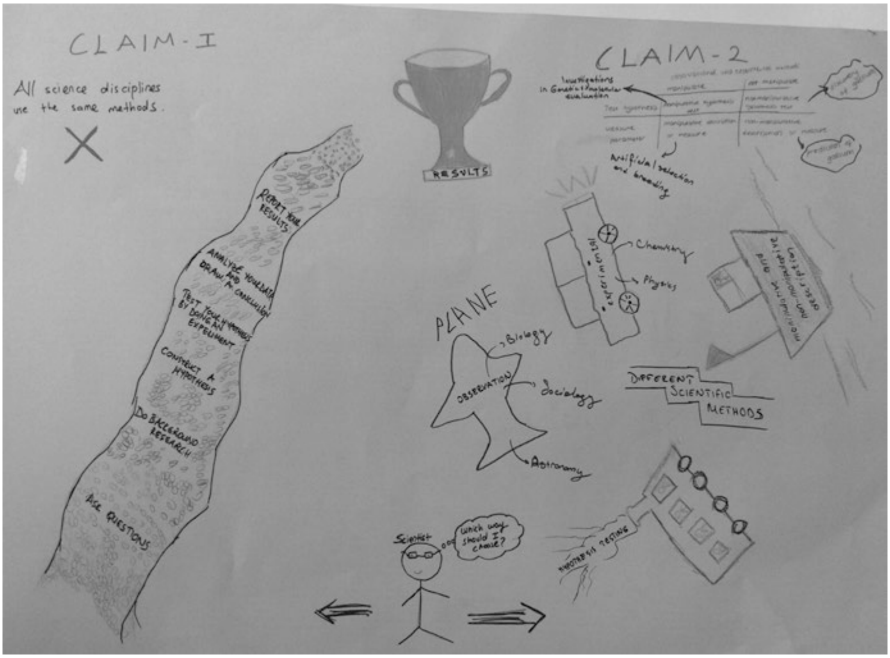


Fig. 21.10 Preservice science teachers' representation of diversity of scientific methods

distinct functions in science. They have explicitly referred to Brandon's matrix to help substantiate Claim 2. Overall, the preservice chemistry teachers used an analogy to talk about scientific methods, drawing on daily life examples and their scientific knowledge. In a subsequent stage, when the group produced lesson plans, they included a figure to show students the different methods used in science (See Fig. 21.11).

Individual interviews were conducted with the preservice teachers to investigate any changes in their view of the various categories, including scientific methods. The analysis of individual pre- and post- interview data indicate a qualitative improvement in preservice teachers' understanding of scientific methods. While their initial ideas about the scientific method and its teaching in science lessons were rather restricted, they became more elaborate and nuanced following the intervention.

Consider the following contrast of the pre- and post- data of one preservice teacher from the case study group:

Pre-intervention

> ***Interviewer:*** *What comes to your mind when I say, "scientific methods"?*
> ***Preservice teacher:*** *I think of things like research and data collection.*
> ***Interviewer:*** *Can you give any examples?*

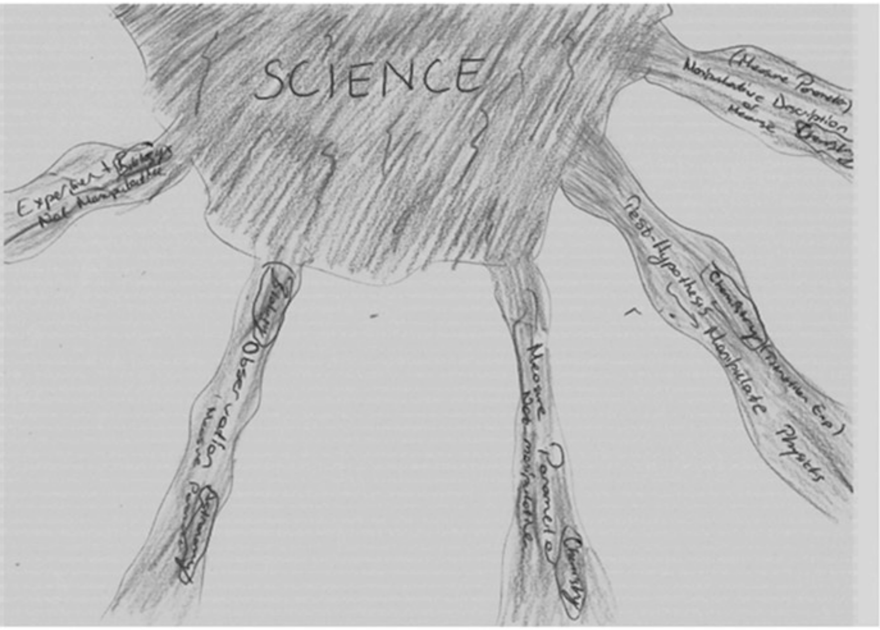


Fig. 21.11 Preservice science teachers' representation of scientific methods in their lesson plans (from Erduran and Kaya, 2019, p. 98)

> ***Preservice teacher:*** *Like doing experiments, collecting data.*
> ***Interviewer:*** *Are scientific methods taught in lessons?*
> ***Preservice teacher:*** *Yes, but they are not tied to everyday life.*

Post-intervention

Preservice teacher: *Methods are like how you make scientific practices come to life. You can't really put scientific methods into a box. Different scientists can develop different methods for what they want to investigate.*

Interviewer: *Do you think scientific methods are taught in science lessons?*

Preservice teacher: *I think they are taught but in a specific framework like you start with a hypothesis and you follow a certain sequence.*

Interviewer: *So how can scientific methods be taught then in lessons?*

Preservice teacher: *We could get students to develop their own methods. In other words, they can determine a topic and propose the investigation themselves.*

The second quote illustrates that the preservice teacher developed in her understanding of the pedagogical aspect of the scientific method following the intervention. Her initial remark was fairly broad and it highlighted the importance of linking the content of lessons to everyday context of the students. In contrast, her post-remarks are more specific about how students can be engaged in active learning of scientific methods. The lesson plans on scientific methods developed by the group seem to corroborate this observation. Overall, quantitative and qualitative data analysis of conducted as part of the teacher education project suggest that the intervention had an overall significant impact on pre-service teachers' views of NOS (Kaya et al. 2019).

21.5 Concluding Remarks

In this chapter, we illustrated how we have used a particular framework on NOS with some visual representations to guide the development of learning resources and teacher education strategies. The original theoretical ideas about FRA (i.e. Erduran and Dagher 2014a) have guided the development of practically- and empirically grounded set of instructional examples. Our illustration of how each visual representation has helped structure each activity will hopefully provide some information and suggestions for how other colleagues and teachers might approach the task of designing resources and strategies. There is now empirical evidence that pre-service teachers' views of NOS and its various dimensions in terms of the FRA categories have improved following a teacher education intervention (Erduran and Kaya 2019; Kaya et al. 2019). The application of FRA to NOS in science education research is relatively new. However, there is now a line of research including completed doctoral (e.g., Cullinane 2018) and master's (e.g., Akgun 2018) dissertations as well as analyses of curriculum documents (e.g., Erduran and Daghert 2014b; Kaya and Erduran 2016) and textbooks (e.g., BouJaoude et al. 2017; McDonald 2017) that are using this approach.

As part of the design of the resources and strategies, we have capitalized on visual tools that provide a summary and a meta-perspective on some key aspects of NOS. Visualization is an important strategy in supporting teachers and students in understanding science (Gilbert et al. 2008). Furthermore, the cognitive basis of representations is well established (Chi 2006), suggesting that some of the representations might promote and indicate quality in reasoning. We have reported elsewhere how pre-service science teachers' visual representations have improved and become more nuanced as a result of participating in an intervention based on the FRA (Erduran & Kaya, 2018). There is also evidence that teachers' metacognitive awareness may be improved through learning about NOS (Abd-El-Khalick and Akerson 2009). The lesson resources relate to the aims and values, methods, practices, knowledge and social-institutional systems of science, making the meta-level aspects explicit through selected components of each category. As explained earlier, our work has provided evidence that the use of these categories in teacher education has made a positive impact on preservice science teachers (e.g. Erduran and Kaya 2018; Kaya et al. 2019). For example, we have presented evidence on how preservice science teachers viewed scientific methods as a diverse set of approaches in science rather than a singular and stepwise and rule-based method. They have further incorporated this idea into their lesson planning (Erduran and Kaya, 2019). The fact that they have incorporated these ideas into their lesson plans is encouraging, as this will be the first step to the implementation of the diversity of methods in teaching.

The findings on scientific methods contribute to our understanding of how the traditional emphasis on the mythical scientific method (e.g. Woodrock 2014) can be surpassed through effective teacher education provision and the development of concrete lesson activities to promote school children's understanding of the diversity of methods in science.

Overall, the chapter contributes to the design of practical student learning and teacher education strategies, using FRA as a guiding framework. It also illustrates the potential of some theoretical perspectives and visual tools for use in educational practice and research. For such perspectives to be useful for practitioners, it is vital that a transformative process takes place, situating the abstract interpretations of NOS in concrete lesson topics and resources that are relevant to the science curriculum. Emerging evidence on the utility and impact of the FRA in framing NOS for science teacher education (e.g. Kaya et al., 2019) is encouraging. Future studies will need to focus on the impact of the strategies and resources on secondary students for whom these approaches have been intended.

References

Abd-El-Khalick, F., & Akerson, V. L. (2009). The influence of meta-cognitive training on preservice elementary teachers' conceptions of nature of science. *International Journal of Science Education, 31*(16), 2161–2184.

Akerson, V. L., Abd-El-Khalick, F., & Lederman, N. G. (2000). Influence of a reflective, explicit activity-based approach on elementary teachers' conceptions of nature of science. *Journal of Research in Science Teaching, 37*(4), 295–317.

Akgun, S. (2018). *University students' understanding of the nature of science*. Unpublished Master's Thesis. Istanbul: Bogazici University.

BouJaoude, S., Dagher, Z. R., & Refai, S. (2017). The portrayal of nature of science in Lebaese 9th grade science textbooks. In C. V. McDonald & F. Abd-El-Khalick (Eds.), *Representations of nature of science in school science textbooks: A global perspective* (pp. 79–97). New York: Routledge.

Brandon, R. (1994). Theory and experiment in evolutionary biology. *Synthese, 99*, 59–73.

Chi, M. T. H. (2006). Methods to assess the representations of experts' and novices' knowledge. In K. A. Ericsson, N. Charness, P. Feltovich, & R. Hoffman (Eds.), *Cambridge handbook of expertise and expert performance* (pp. 167–184). Cambridge: Cambridge University Press.

Cullinane, A. (2018). *Incorporating nature of science into initial science teacher education.* Unpublished PhD dissertation. University of Limerick, Ireland.

Cullinane, A., Erduran, S., & Wooding, S. J. (2019). Investigating the diversity of scientific methods in high-stakes chemistry examinations in England. *International Journal of Science Education*. https://doi.org/10.1080/09500693.2019.1666216.

Davies, R. (1989). The creation of new knowledge by information retrieval and classification. *Journal of Documentation, 45*(4), 273–301.

Erduran, S., & Mugaloglu, E. (2013). Interactions of economics of science and science education: Investigating the implications for science teaching and learning. *Science & Education, 22*(10), 2405–2425.

Erduran, S., & Kaya, E. (2019). *Transforming teacher education through the epistemic core of chemistry: Empirical evidence and practical strategies*. Dordrecht: Springer.

Erduran, S. (Ed.). (2019). *Argumentation in chemistry education: Research, policy and practice*. London: Royal Society of Chemistry.

Erduran, S., Dagher, Z., & MacDonald, C. (2019). Contributions of the family resemblance approach to nature of science in science education: A review of emergent research and development. *Science & Education, 28*(3–5), 311–328.

Erduran, S., & Kaya, E. (2018). Drawing nature of science in pre-service science teacher education: Epistemic insight through visual representations. *Research in Science Education, 48*(6), 1133–1149.

Erduran, S., Ozdem, Y., & Park, J. Y. (2015). Research trends on argumentation in science education: A journal content analysis from 1998–2014. *International Journal of STEM Education, 2*(5), 12. https://doi.org/10.1186/s40594-015-0020-1.

Erduran, S., & Dagher, Z. (2014a). *Reconceptualizing the nature of science for science education: Scientific knowledge, practices and other family categories*. Dordrecht: Springer.

Erduran, S., & Dagher, Z. (2014b). Regaining focus in Irish junior cycle science: Potential new directions for curriculum development on nature of science. *Irish Educational Studies, 33*(4), 335–350.

Erduran, S., & Jimenez-Aleixandre, M. P. (Eds.). (2007). *Argumentation in science education: Perspectives from classroom-based research*. Dordrecht: Springer.

Gilbert, J. K., Reiner, M., & Nakhleh, M. (Eds.). (2008). *Visualization: Theory and practice in science education*. Dordrecht: Springer.

Irzik, G., & Nola, R. (2014). New directions for nature of science research. In M. Matthews (Ed.), *International handbook of research in history, philosophy, and science teaching* (pp. 999–1021). Dordrecht: Springer.

Kaya, E., Erduran, S., Aksoz, B., & Akgun, S. (2019). Reconceptualised family resemblance approach to nature of science in pre-service science teacher education. *International Journal of Science Education, 41*(1), 21–47.

Kaya, S., Erduran, S., Birdthistle, N., & McCormack, O. (2018). Looking at the social aspects of nature of science in science education through a new Lens: The role of economics and entrepreneurship. *Science & Education, 27*(5–6), 457–478.

Kaya, E., & Erduran, S. (2016). From FRA to RFN, or how the family resemblance approach can be transformed for curriculum analysis on nature of science. *Science & Education, 25*(9–10), 1115–1133.

Matthews, M. (2012). Changing the focus: From nature of science (NOS) to features of science (FOS). In M. S. Khine (Ed.), *Advances in nature of science research* (pp. 3–26). Dordrecht: Springer.

McComas, W. F. (1998). The principal elements of the nature of science: Dispelling the myths. In W. F. McComas (Ed.), *The nature of science in science education* (pp. 53–70). Netherlands: Khwer Academic Publishers.

McDonald, C. V. (2017). Exploring representations of nature of science in Australian junior secondary school science textbooks: A case study of genetics. In C. V. McDonald & F. Abd-El-Khalick (Eds.), *Representations of nature of science in school science textbooks: A global perspective* (pp. 98–117). New York: Routledge.

Toulmin, S. (1958). *The uses of argument*. Cambridge, UK: Cambridge University Press.

Woodrock, B. A. (2014). “The Scientific Method” as myth and ideal. *Science & Education, 23*, 2069–2093.

Yeh, Y., Erduran, S., & Hsu, Y. S. (2019). Investigating coherence on nature of science in the science curriculum documents from Taiwan. *Science & Education, 28*(3–5), 291–310.

Chapter 22
Arguing to Learn and Learning to Argue with Elements of Nature of Science

Hasan Deniz, Lisa Borgerding, and Elif Adibelli-Sahin

22.1 Introduction

The term “epistemology” in a philosophical context refers to “the origin, nature, limits, methods, and justification of human knowledge” (Hofer 2002, p. 4) and nature of science refers to the epistemology of science (Lederman and Abd-El-Khalick 1998; Lederman 2007). Therefore, acquiring sophisticated conceptions of nature of science require people to form an informed opinion about the origin, methods, limits, and justification of scientific knowledge. This underscores the need to educate our students not only about the currently accepted theories, laws, models, and major concepts in a scientific discipline but also about how we know what we know in science, and why we accept the scientific worldview (Driver et al. 1996). Acceptance of scientific worldview does not mean the categorical rejection of other ways of knowing, but it means to understand the affordances and limitations of science in explaining natural phenomena.

Understanding the nature of science (NOS) has been considered an important part of scientific literacy and, therefore, teaching NOS has been endorsed at all grade levels by the aforementioned major science education reform efforts in the United States.

Nature of science (NOS) refers to values and beliefs specific to scientific knowledge and its development (Lederman 2007). It was widely accepted that there is no

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_22

single agreed-upon single definition of NOS among philosophers of science, historians of science, scientists, and science educators, but a substantial number of NOS aspects are uncontroversial and recommended for inclusion in K-16 science education. These NOS aspects include but are not limited to conceptions that scientific knowledge is empirical, tentative, subjective, inferential, socially and culturally embedded, and depends upon human creativity and imagination. Clearly, several NOS aspects are drawn upon in scientific argumentation: supporting claims with empirical evidence; recognizing how inferentially, subjectively, and socioculturally derived alternative claims exist; and accepting claims tentatively based on sociocultural norms within the scientific community.

The use of argumentation framework in science teaching provides affordances to expose students to the epistemic criteria of science that provide a basis for students to develop nature of science conceptions that are promoted by major science education reform documents (American Association for the Advancement of Science [AAAS] 1993; National Research Council [NRC] 1996, 2012; NGSS Lead States 2013). The argumentation framework requires the coordination of scientific claims and data through meaningful justifications (warrant). An important task for science educators, therefore, is to develop lessons or activities that will allow teachers to teach NOS conceptions through argumentation framework. The nature of science activity described in this chapter is organized around argumentation framework developed by Toulmin (1958). According to Toulmin, the basic components of an argument are claims, data, warrants, and backings. Claims are unwarranted assertions that a person believes to be true. The data component of the argument includes measurements, observations, or findings from other studies. The warrant component of the argument justifies a person's choice of data and provides a link between the claim and the data. The backing component provides an additional reasoning that supports the warrant.

The use of argumentation framework in teaching NOS conceptions is consistent with the practice of scientists and this approach can be supported with cases from history of science. Professional argumentation can be considered as the primary activity of scientists (Bazerman 1988) as they debate their conclusions with others in the scientific community. The history of science abounds with examples of scientific argumentation. Consider the example of Newton. After a careful analysis of Newton's journal articles over a certain period of time, Bazerman (1988) concluded that Newton presented his experiments to persuade the reader to accept the validity of his interpretations by changing the actual sequence of his experiments and using a variety of rhetorical devices. In other words, Newton purposefully changed the sequence of his experiments in his writing to make his case.

Similarly, Galileo resorted to rhetorical devices to convince his audience to reject the claim that the apparent sizes of Venus and Mars do not change noticeably during the year (Chalmers 2013). It is clear that Galileo had robust telescopic evidence to reject this claim; however, simply presenting the evidence was not enough. Galileo vigorously needed to argue against the common claim that the apparent sizes of Venus and Mars do not change by using his superior telescopic observations. In addition, Galileo also needed to convince his audience for the superiority of the

Copernican system over the Ptolemaic system by giving priority to his telescopic observations over naked-eye observations. In sum, the data, of themselves, do not establish the claim that the apparent sizes of Venus and Mars change during the year; the data require a warrant/justification/reasoning connecting the claim and the evidence.

Argumentation is also vital in biology. A close examination of Watson and Crick's (1953) iconic paper titled *Molecular Structure of Nucleic Acids: A Structure for Deoxyribonucleic Acid* reveals the use of such argumentative language. In the excerpt that follows, Watson and Crick describe existing work suggesting triple helix DNA models in circulation at the time and allude to the larger scientific community and typical avenues for sharing work. They then specifically cite multiple lines of evidence to support their claim of a double helix while also using multiple lines of evidence to rebut the possible but unsupported alternative triple helix model. These historical examples illustrate the importance of scientific argumentation to communicate and advance scientific research (Fig. 22.1).

We believe that the use of argumentation framework to construct explanations of the natural world has a great potential to expose students to the epistemic criteria of science that provide a basis for students to develop nature of science conceptions that are promoted by major science education reform documents. In this chapter, we capitalize on affordances of argumentation framework to teach NOS aspects. Thus, we present an activity designed to explicitly introduce NOS conceptions to students by engaging them in a NOS activity organized around an argumentation framework.

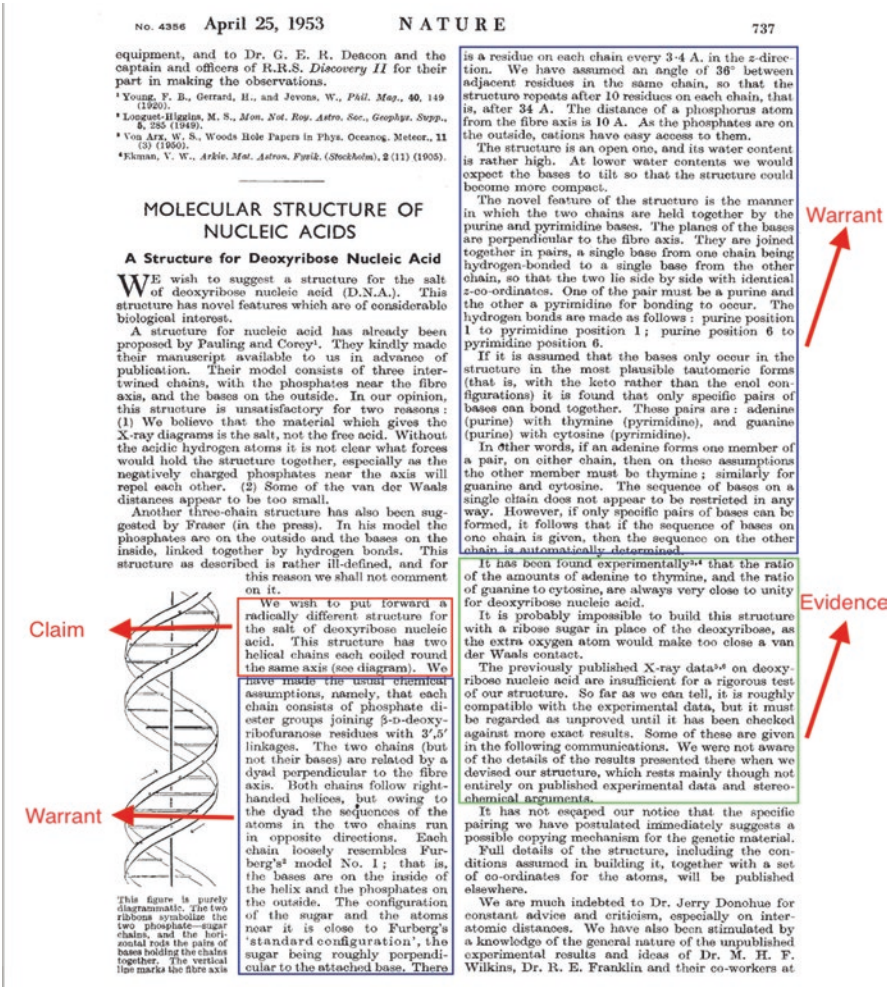
22.2 The Bottle Activity

The bottle activity we feature here is similar to many such activities that are described in this book. Black box activities draw students' attention and motivate them to come up with plausible hypotheses or inferences for their observations. Then students are asked to explain their thought processes by drawing a proposed model representing what is happening inside the bottle. Students are then asked to construct their own models to test their hypotheses or inferences.

In this chapter, we aimed to address empirical, creative, inferential, subjective and collaborative NOS aspects, and the demarcation criteria for science (bounded NOS aspect or "science has limits") with varying degrees of sophistication across grade levels. In the explicit reflection that concludes this activity, students are prompted to reflect on these NOS aspects and their engagement in scientific argumentation.

Level: Upper elementary, middle, or high school
Materials:

- A nontransparent bottle or a bottle covered or painted,
- A rubber stopper,
- A piece of string or yarn



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equipment, and to Dr. G. E. R. Deacon and the captain and officers of R.R.S. *Discovery II* for their part in making the observations.

[1] Young, F. B., Gerrard, H., and Jevons, W., *Phil. Mag.*, **40**, 149 (1920).
[2] Longuet-Higgins, M. S., *Mon. Not. Roy. Astro. Soc., Geophys. Supp.*, **5**, 285 (1949).
[3] Von Arx, W. S., Woods Hole Papers in Phys. Oceanog. Meteor., **11** (3) (1950).
[4] Ekman, V. W., *Arkiv. Mat. Astron. Fysik. (Stockholm)*, **2** (11) (1905).

MOLECULAR STRUCTURE OF NUCLEIC ACIDS

A Structure for Deoxyribose Nucleic Acid

WE wish to suggest a structure for the salt of deoxyribose nucleic acid (D.N.A.). This structure has novel features which are of considerable biological interest.

A structure for nucleic acid has already been proposed by Pauling and Corey[1]. They kindly made their manuscript available to us in advance of publication. Their model consists of three intertwined chains, with the phosphates near the fibre axis, and the bases on the outside. In our opinion, this structure is unsatisfactory for two reasons: (1) We believe that the material which gives the X-ray diagrams is the salt, not the free acid. Without the acidic hydrogen atoms it is not clear what forces would hold the structure together, especially as the negatively charged phosphates near the axis will repel each other. (2) Some of the van der Waals distances appear to be too small.

Another three-chain structure has also been suggested by Fraser (in the press). In his model the phosphates are on the outside and the bases on the inside, linked together by hydrogen bonds. This structure as described is rather ill-defined, and for this reason we shall not comment on it.

We wish to put forward a radically different structure for the salt of deoxyribose nucleic acid. This structure has two helical chains each coiled round the same axis (see diagram). We have made the usual chemical assumptions, namely, that each chain consists of phosphate diester groups joining β-D-deoxyribofuranose residues with 3′,5′ linkages. The two chains (but not their bases) are related by a dyad perpendicular to the fibre axis. Both chains follow right-handed helices, but owing to the dyad the sequences of the atoms in the two chains run in opposite directions. Each chain loosely resembles Furberg's[2] model No. 1; that is, the bases are on the inside of the helix and the phosphates on the outside. The configuration of the sugar and the atoms near it is close to Furberg's 'standard configuration', the sugar being roughly perpendicular to the attached base. There is a residue on each chain every 3·4 A. in the z-direction. We have assumed an angle of 36° between adjacent residues in the same chain, so that the structure repeats after 10 residues on each chain, that is, after 34 A. The distance of a phosphorus atom from the fibre axis is 10 A. As the phosphates are on the outside, cations have easy access to them.

This figure is purely diagrammatic. The two ribbons symbolize the two phosphate—sugar chains, and the horizontal rods the pairs of bases holding the chains together. The vertical line marks the fibre axis

The structure is an open one, and its water content is rather high. At lower water contents we would expect the bases to tilt so that the structure could become more compact.

The novel feature of the structure is the manner in which the two chains are held together by the purine and pyrimidine bases. The planes of the bases are perpendicular to the fibre axis. They are joined together in pairs, a single base from one chain being hydrogen-bonded to a single base from the other chain, so that the two lie side by side with identical z-co-ordinates. One of the pair must be a purine and the other a pyrimidine for bonding to occur. The hydrogen bonds are made as follows: purine position 1 to pyrimidine position 1; purine position 6 to pyrimidine position 6.

If it is assumed that the bases only occur in the structure in the most plausible tautomeric forms (that is, with the keto rather than the enol configurations) it is found that only specific pairs of bases can bond together. These pairs are: adenine (purine) with thymine (pyrimidine), and guanine (purine) with cytosine (pyrimidine).

In other words, if an adenine forms one member of a pair, on either chain, then on these assumptions the other member must be thymine; similarly for guanine and cytosine. The sequence of bases on a single chain does not appear to be restricted in any way. However, if only specific pairs of bases can be formed, it follows that if the sequence of bases on one chain is given, then the sequence on the other chain is automatically determined.

It has been found experimentally[3,4] that the ratio of the amounts of adenine to thymine, and the ratio of guanine to cytosine, are always very close to unity for deoxyribose nucleic acid.

It is probably impossible to build this structure with a ribose sugar in place of the deoxyribose, as the extra oxygen atom would make too close a van der Waals contact.

The previously published X-ray data[5,6] on deoxyribose nucleic acid are insufficient for a rigorous test of our structure. So far as we can tell, it is roughly compatible with the experimental data, but it must be regarded as unproved until it has been checked against more exact results. Some of these are given in the following communications. We were not aware of the details of the results presented there when we devised our structure, which rests mainly though not entirely on published experimental data and stereochemical arguments.

It has not escaped our notice that the specific pairing we have postulated immediately suggests a possible copying mechanism for the genetic material.

Full details of the structure, including the conditions assumed in building it, together with a set of co-ordinates for the atoms, will be published elsewhere.

We are much indebted to Dr. Jerry Donohue for constant advice and criticism, especially on interatomic distances. We have also been stimulated by a knowledge of the general nature of the unpublished experimental results and ideas of Dr. M. H. F. Wilkins, Dr. R. E. Franklin and their co-workers at

Fig. 22.1 An annotated excerpt from Watson and Crick (1953) paper published in Nature

22.2.1 *Procedure/Scenario*

22.2.1.1 Phase 1: Demonstration/Observations

Before we perform the demonstration depicted in Fig. 22.2, the instructor asks students to make careful observations of what is about to happen. The instructor then performs the demonstration and prompts students to record as many observations as possible about the demonstration.

The students realize that the bottle does not fall upon release. At this point, the students are puzzled to see that the bottle does not fall, and they ask to repeat the demonstration. The instructor can repeat the demonstration several times.

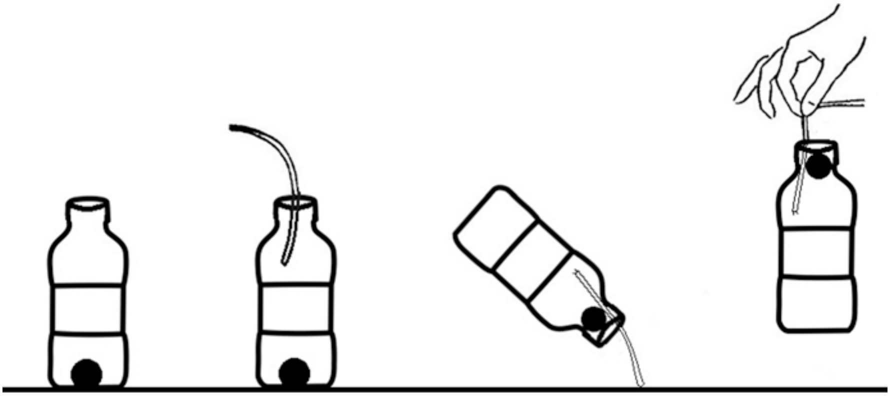

Fig. 22.2 The bottle demonstration

We recommend that students should work in small groups responding to the following question, “Can you figure out what is inside the bottle?” The instructor then asks students to spend a few minutes brainstorming suggestions for what is going on inside and how they could find out without actually opening it using their observations.

After students complete their brainstorming, the instructor asks each group to list 3–4 observation statements on the board. The instructor makes sure that students do not mix their observations statements with their inferences. Observations are made with five senses. Inferences require cognitive processing of various observations in order to reach a conclusion. While observations are immediately accessible to our five senses, inferences utilize background knowledge, even implicitly, and are not immediately accessible to our five senses.

Statements such as “The bottle is covered with black” and “The instructor tilted the bottle once” are observations.

22.2.1.2 Phase 2: Inferring a Model/Making a Claim

The instructor then prompts students to draw a diagram model for how they think the mechanism inside the bottle works. Because the bottle is covered, students do not see what is inside the bottle during the demonstration. Therefore, they have to use their observations, creativity, and prior knowledge to infer a model of the interior of the bottle. The instructor reminds the students to develop models consistent with their observations. Students take about 10 min to discuss their emerging inferences and make model drawings of what is inside the bottle. Each group has to reach a consensus on their strongest model drawing.

At this point, we use the following argumentation scaffolds guiding students to making a scientific claim about the bottle model. The following prompts are used:

Claim-What can we claim that we know?
We claim that ____

Data-How do we know (what evidence exists)?
Our evidence for this claim is ______________________________________
____

Other evidence for this claim is
____
____

Warrant-How does evidence support our claim?
Our evidence supports our claim because ______________________________

Sample Student Response:
We claim that *there is an object, which can move inside the bottle.*

Our evidence for this claim:

1. The instructor tilted the bottle's neck downward.
2. The bottle did not fall after tilting.
3. The bottle fell if the instructor did not tilt the bottle's neck downward.

Warrant:

> Our evidence supports our claim because *after tilting the moving object presses the string against the bottleneck, which makes the bottle hanging possible.*

22.2.1.3 Phase 3: Alternative Explanations

The instructor then asks student groups to share their inferred model by drawing these models on the board. Although the students are curious about what other groups are drawing, we remind them to draw their own consensus model on the board. After the models are all drawn, we use this whole group conversation to ask students if every group inferred the same model. We ask students, "Did every group develop the same model? What is similar and different across these models?" Most students realize that different groups developed different models, and these multiple models are largely consistent with the available observations. During the debriefing phase at the end of the bottle activity, we can use this opportunity to point out that different groups made and gave priority to different kinds of observations in the development of their models and point out that this represents an example of subjectivity.

We also ask students if they could do anything to test or distinguish between any of the inferred models.

We prompt students to complete the next part of their argumentation task by responding to the next argumentation prompts.

Anticipating a Counter-Argument & Rebuttal?

Someone might also try to explain what we observed by saying ____________________, but we do not support that explanation for these reasons: ____________________________.

22.2.1.4 Phase 4: Explicit Reflective Debriefing for NOS and Argumentation

At the end of the activity, it is essential to *explicitly* discuss the target NOS aspects and scientific argumentation that was embedded in this activity. For this purpose, we recommend to use a poster making NOS aspects and their descriptions visible to the students.

Using the poster and the question prompts in Table 22.1, the instructor explicitly asks reflection questions targeting the various NOS aspects.

Building on this explicit reflective NOS discussion, we then use this opportunity to prompt students to reflect on how they engaged in scientific argumentation throughout this process. We ask questions such as:

- What claims did you make about this mysterious bottle?
- What lines of evidence did you use to support those claims?
- Did you use multiple lines of evidence?
- Were some lines of evidence stronger than others?
- Did other groups make other claims about the model?
- How could you determine if some of the inferred model claims were better or worse than the others?
- Were some of the models more or less consistent with evidence?

22.3 Conclusion

We found the bottle activity to be an effective method of introducing both NOS aspects and argumentation to different audiences such as K-12 students and pre-service and in-service teachers. This activity provides the opportunity for students to improve their NOS conceptions while they practice their argumentation skills. The activity allows teachers to target more concrete NOS aspects such as empirical, creative, and inferential NOS aspects with elementary students while it allows teachers to explicitly teach more abstract NOS aspects such as subjective, collaborative, and bounded NOS aspects to older audiences.

Table 22.1 Reflective NOS questions and explicit NOS explanations

NOS aspect	Reflective questions	NOS explanation
Empirical	What did you base your inferred models on? What was your "data"? Were you able to support your model with "evidence"?	You did not make up your inferences/claims. Your inferences/claims are based on your observations. When you use your observations to justify your claims or form your inferences these observations become your *evidence*. In science, all claims should be backed up with evidence.
Creative	How did your group develop your model? Did you use your creativity and imagination?	Coming up with a claim/inference about what is inside the bottle requires creativity and imagination as well as making observations. Without the creativity and imagination scientists cannot make the leap from observation to inference/claim.
Inferential	How were your observations different from your inferences? How did you make inferences from your observations?	Scientists use both observations and inferences. Observation is the process of using the five senses to gather information about the natural world. Inference is the process of reaching logical conclusions based on observations.
Subjective	Did every group develop the same models? Why did some groups develop different models even though they made similar observations? What background knowledge did your group use when you were developing your model?	Each group came up with a different inference/claim explaining what is inside the bottle. Similarly, scientists can have different explanations for the same phenomenon. Therefore, scientific knowledge is not entirely objective. This means that personal values, prior knowledge and experience affect what scientists study and how they do science.
Collaborative	How did your group work together to develop your model? How did viewing other groups' models affect your ideas about your own model?	You worked in groups to come up with your claims/inferences. You also reviewed other group's claims/inferences and criticized them. Similarly, Scientists work in teams or work alone, but all communicate with each other, share their knowledge, and critically review each other's work.
Bounded "Science has limits"	Could ANY inferred model work? Why not? What if a person claimed that there was an invisible genie inside the model or magic making it work this way? Could science test that claim?	Obviously, this person would not be able collect any evidence to support his or her claim. Similarly, he/she would not be able to collect any evidence to refute the claim. If scientists cannot collect any evidence to test a claim, this claim cannot be called scientific. In other words, all scientific claims should be *falsifiable.* Science cannot answer all questions. Science is appropriate for understanding the natural world but it cannot answer questions related to supernatural, art, philosophy, religion, or ethics.

References

American Association for the Advancement of Science. (1993). *Benchmarks for science literacy: Project 2061*. New York: Oxford University Press.

Bazerman, C. (1988). *Shaping written knowledge: The genre and activity of the experimental article in science*. Madison: University of Wisconsin Press.

Chalmers, A. F. (2013). *What is this thing called science?* (4th ed.). Indianapolis: Hackett Publishing.

Driver, R., Leach, J., Millar, R., & Scott, P. (1996). *Young people's images of science*. Buckingham: Open University Press.

Hofer, B. K. (2002). Personal epistemology as a psychological and educational construct: an introduction. In B. K. Hofer & P. R. Pintrich (Eds.), *Personal epistemology: the psychology of beliefs about knowledge and knowing* (pp. 3–14). Mahwah: Lawrence Erlbaum.

NGSS Lead States. (2013). *Next generation science standards: For states, by states*. Washington, DC: The National Academies Press.

Lederman, N. G. (2007). Nature of science: Past, present, and future. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research in science education* (pp. 831–879).

Lederman, N. G., & Abd-El-Khalick, F. (1998). Avoiding de-natured science: Activities that promote understanding of the nature of science. In W. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 41–52). Dordrecht: Kluwer Academic.

National Research Council. (1996). *National science education standards*. Washington, DC: National Academy Press.

National Research Council (NRC). (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: National Academies Press.

Toulmin, S. (1958). *The uses of argument*. Cambridge: Cambridge University Press.

Watson, J. D., & Crick, F. H. C. (1953). Molecular structure of nucleic acids. *Nature, 171*, 737–738.

Chapter 23
Considering the Classroom Assessment of Nature of Science

Deborah Hanuscin, Mojtaba Khajeloo, and Benjamin C. Herman

23.1 Introduction

Although there have been both contributions and debate among science educators regarding the best way to assess understanding of NOS for research purposes (Chen 2006; Chen et al. 2013; Elby and Hammer 2001; Lederman et al. 2002), teachers' classroom strategies for assessing their students' understanding of NOS have received only minimal attention. Studies have examined the utility of explicit approaches to teaching about NOS, which are defined as approaches in which NOS is "… intentionally planned for, taught, *and assessed* (emphasis added)" (Lederman et al. 2001, p. 137), yet this latter component (assessment of NOS) is often not addressed in research that examines teachers' NOS instruction.

If we define effective NOS instruction as teaching that positively impacts student understanding of key NOS principles, then it logically follows that assessment of student learning about NOS serves as an important component of teachers' classroom practice (Clough 2006; 2011; Hanuscin et al. 2010). Teachers' classroom assessment practices play an important role in informing their instruction and also communicate to students what is important to learn. Despite numerous examples of NOS teaching strategies and lessons (e.g., Bell 2008), descriptions of effective

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_23

classroom assessment practices related to NOS are lacking—both in the research literature and in the practitioner literature (Aydin et al. 2013; Cite and Hanuscin 2014). In this chapter, we describe what little we do know about teachers' classroom assessment of NOS. We then consider how various perspectives in the literature might frame our thinking about how to approach classroom assessment of NOS. Finally, we discuss possible next steps to address the current gaps in our knowledge from the perspective of both research and practice.

We specifically confine our focus in this chapter to *classroom assessment* rather than research instruments and practices for assessing NOS for several reasons. First, there exist several in-depth examinations of NOS assessment approaches already (cf. Abd-El-Khalick 2014). Second, the use of such instruments by classroom teachers would be inappropriate not only because it could potentially invalidate their use for future research were students exposed to the instruments prior but also because these instruments often require specialized technical knowledge and understanding of NOS beyond what teachers may possess. Third, because they are designed for research purposes, they may be impractical for other purposes, such as use by classroom teachers to evaluate specific learning targets related to NOS. Finally, their use impinges on alignment with the particular construct of NOS underlying the instrument and the learning outcomes desired by the teacher. This latter point is one we will consider in further depth in this chapter in relation to what classroom teachers might consider to be outcomes of NOS both possible and worthy to assess.

23.2 General Practices Related to Teachers' Classroom NOS Assessment

The few existing studies that include substantive evidence of teachers' classroom assessment practices for NOS (though not as a central focus of the research) suggest that teachers typically neglect formally assessing students' NOS learning (Abd-El-Khalick et al. 1998; Hanuscin et al. 2010; Herman et al. 2013; Wahbeh and Abd-El-Khalick 2014). Rather, these studies indicate that teachers more often rely on informal assessment of student NOS learning based on questioning and discussion in class (Schwartz and Lederman 2002) or their intuition about how the lesson "worked" with students (Bartholomew et al. 2004). Furthermore, Ryder and Leach (2008) report that teachers' assessment of students' ideas about NOS often stops short with simply eliciting their ideas. They found when questioning students about NOS, teachers generally accepted all responses, offering non-evaluative comments and teachers struggled to work with their students' ideas in meaningful ways. Such efforts that merely elicit students' ideas fall short of the goals of formative assessment to inform instruction and support student learning needs (Black and Wiliam 1998).

Overall, the literature provides few examples of teachers who assess students' learning about NOS in ways that are parallel to how they assess other science learning outcomes (Herman et al. 2013). Several studies reveal that teachers who *do* formally assess NOS have done so through more traditional and decontextualized means. For example, Lederman and colleagues noted a teacher who wrote "…two exam questions aligned with his two objectives on scientific models (inference) and tentativeness" (2001, p. 152). Similarly, Bartholomew et al. (2004) described teachers' intentions (though not carried out) to test students' understanding of the words "observation" and "inference." In contrast, Herman et al. (2013) showed that teachers considered to be "high NOS implementers" assessed students' learning about NOS in a variety of contexts (from decontextualized through highly contextualized settings), while others focused on more superficial and decontextualized assessment.

Some researchers have attributed teachers' failure to assess their students' ideas about NOS to a "discrepancy between [their practices and] stated belief in the importance of teaching NOS" (Abd-El-Khalick et al. 1998, p. 427). This viewpoint is implicit in recommendations that NOS be included in high-stake assessments, since these "send clear messages to teachers about what to emphasize in their instruction" (Clough and Olson 2008, p. 145). Others (Hanuscin et al. 2010) suggest that teachers' lack of NOS assessment may actually be a reflection of their lack of knowledge of strategies for assessing students' ideas about NOS, difficulty in determining what to assess in regard to student learning about NOS, and the belief that NOS is something that cannot be assessed. That is, they lack knowledge of assessment, which is as a component of teachers' pedagogical content knowledge (PCK) for teaching NOS (Hanuscin 2013). A confounding issue is that teachers looking for existing resources to enhance their PCK in this manner encounter a lack of examples of NOS assessment in the practitioner literature, which—while rich in examples of activities and strategies for teaching about NOS—includes few, if any, examples of NOS assessment tools or practices (Aydin et al. 2013; Cite and Hanuscin 2014). Similarly, the curriculum teachers are provided may identify NOS as a learning goal, but not emphasize NOS explicitly in the assessments (Ryder and Leach 2008).

While significant efforts have been made over the past decades to develop *research instruments* that provide a valid and meaningful assessment of respondents' ideas about NOS and that are appropriate for different populations and scales (Hodson 2009), there have been few similar efforts to develop *classroom assessment instruments* described in the literature. An exception is the work of Akerson et al. (2010) who utilized a participatory action research approach with teachers to develop NOS assessments. Another approach has been offered by Loughran et al. (2003) who attempted to develop a paper-and-pencil test for high school students to evaluate the impacts of a unit of study designed to illustrate for students what it was like to "work like a scientist." The researchers found this challenging, in that the nature of the tasks they developed actually shaped students' responses:

> In the first part of the test, which we deliberately left open ended to elicit students' true reaction, they framed their responses according to content and, as noted earlier, perhaps sought to second-guess what they thought might be expected of them…. In the second part, where we signaled the aspects of science of interest to us, students responded in ways that indicated their understanding of our intention. Consequently, the responses elicited may not in fact be complete representations of what students really think (2003, p. 14–15).

Loughran and colleagues concluded their work by emphasizing the complexity of the task of assessing students' learning about NOS, but also the importance of doing so. While subsequent work has echoed this importance, there has been little movement toward addressing this gap. This is striking, given the great deal of attention paid to NOS instruction—because assessment provides teachers with important feedback that can both inform and help them evaluate the efficacy of their instruction. Indeed, the lack of such assessment tools may be one factor mediating teachers' effectiveness in teaching about NOS (Hanuscin et al. 2010; Wahbeh and Abd-El-Khalick 2014).

This chapter is a first step toward addressing that gap, by considering current perspectives on what it means for students to understand NOS, and the implications of those perspectives for the design of classroom assessment. We extend our discussion as well to the implications for much-needed research on classroom assessment practices for NOS.

23.3 What Does it Mean to Understand NOS?

As Ford (2008) suggests, how we measure a particular learning outcome reflects how we think about and conceptualize it. In examining NOS classroom assessments, therefore, it is crucial to begin by clarifying what it is we are assessing when we speak of gauging "students" understanding of NOS. In the following sections of this chapter, we share three different perspectives on what it means to "understand NOS." Our intent here is not to firmly demarcate these perspectives of NOS understanding and elevate one view at the expense of another. One could argue that they appear to have somewhat overlapping and "fuzzy" borders, and collectively provide important implications for NOS assessment (Allchin et al. 2014). Rather, we hope to consider each critically from the perspective of classroom practitioners, exploring the extent to which each could potentially inform and shape the design of classroom NOS assessments, and identifying implications for research and practice.

23.4 Understanding Aspects of NOS

An extensive body of literature on NOS has focused largely on declarative knowledge; what individuals can articulate *about* science and its products. Driver, Leach, Millar, and Scott exemplify this view of understanding the nature of science by describing it as:

> …ideas which a student has about science, as distinct from their ideas about the natural world itself, how the body of public knowledge called science has been established and is added to; what our grounds are for considering it reliable knowledge; how the agreement which characterizes much of science is maintained (1996, p.13)

This particular way of defining an understanding of NOS is reflected in the teaching of "aspects of NOS" or "NOS tenets"—statements about science such as "science is based on empirical evidence" (McComas and Olson 1998) and in confronting myths about the nature of science (McComas 1996). For example, a student who understands NOS would understand human elements of science, such as creativity being vital to scientific work. Indeed, there is an extensive body of work on explicit approaches to teaching students about NOS (cf. researchers including Abd-El-Khalick, Akerson, Bell, & Lederman) and in which assessment instruments probe students' ideas related to these tenets. Research has reinforced the notion that having students simply engage in inquiry, for instance, is not enough to promote understanding of NOS (Roth and Roychoudhury 1993), and that ideas about NOS should be an explicit part of science investigations and laboratory instruction (Ozgelen et al. 2013).

Throughout the relevant literature, NOS is referenced as a cognitive outcome of instruction by researchers (e.g., Abd-El-Khalick, et al. 1998). This perspective has appeal in terms of classroom assessment, as it places NOS on equal footing with other content students will learn, and the assessment of declarative knowledge in other domains could provide models for how to approach assessing NOS from this perspective. However, in such studies, researchers tend to focus on students' *views* or *perspectives* on NOS rather than *understanding*. For example, respondents to one popular research instrument are reminded, "there are no right or wrong answers to any item" (Lederman et al. 2002, p. 511), and researchers are specifically cautioned against using the instrument as a summative assessment (i.e., considering student answers "correct" or "incorrect"). Rudolph (2000) referred to this situation in terms of the existence of a multitude of perspectives of NOS presented by historians, sociologists, and philosophers of science (thus no one definition of "NOS") as creating a "paralysis of practical action" for teachers. Ryder and Leach (2008) emphasize the view that accepting all students' ideas about NOS as equally valid does little to inform instruction and does nothing to help move students toward the kind of shared understanding about how science works that we value. The focus on "views" of NOS, then, is inconsistent with tasks with which teachers are charged—the summative evaluation of student learning and the assigning of grades.

23.5 Nature of Science as a "Grasp of Practice"

Salter and Atkins (2014) found that students' declarative knowledge about the NOS is not a reliable measure of students' ability to engage productively in scientific practices and vice versa. This latter finding is bolstered by research showing scientists, who arguably engage productively in scientific inquiry, may fail to articulate an "informed" view of the nature of science (Schwartz and Lederman 2008). A second conceptualization of what it means to understand NOS proposed by Ford (2008) addresses this conundrum. This perspective prioritizes the citizenship ability to appropriately react to scientific claims, not an ability to articulate ideas about NOS. The reasoning resources that enables one to do this constitutes a "grasp of practice." As Ford explains:

> … appropriate reactions to scientific claims stem from knowing how, under what circumstances, and why to critique them, and an ability to construct scientific claims rests upon the same reasoning resource (2008, p. 150).

The notion of "practice" within the notion of "grasp of practice" appeals to what scientists do and why—though this may be tacit knowledge. Students develop a "grasp" of scientific practice through participating appropriately in scientific discourses and activities and constructors and critiquers of claims in the science classroom. This view draws on sociocultural learning theories such as internalization (e.g., Vygotsky 1978) and enculturation (e.g., Rogoff 2003) to link students' epistemic developments and their social interactions. Similarly, Duschl (2008) and Jimenez-Aleixandre (2014) contend that argumentation in science classrooms should emphasize two convergent aspects: "social negotiation (e.g., how to critique, debate, and evaluate an argument) and epistemic understanding of argument (e.g., what counts as data, evidence, and claim, and the relationships between these components)" (cited in Chen et al. 2016, p. 278).

Ford points out that assessment of NOS understanding as declarative knowledge poses a challenge since "[s]cientists or students who have a grasp of practice may or may not be able to translate this knowing into an explicit form for such an assessment" (2008, p. 173). Grasp of practice, in contrast, shifts the focus of the learning goal from knowing *about* to knowing *how*. This perspective is consistent with the focus of recent reforms in science education, such as the *Next Generation Science Standards* (NGSS Lead States 2013), which emphasize student engagement in science and engineering practices.

Rather than seeking evidence of student understanding of NOS from what students are able to articulate about NOS, Duschl and Grandy (2012) argued that learners' understanding of NOS is evident in their own engagement in and enactment of scientific practices. For instance, Ford provided an example in which students were asked to design and execute an experiment to answer a novel question, "noting features of their performances that suggest they had attained a grasp of practice" (2008, p.161). While this has appeal, the implications for teachers' classroom assessment of students "grasp of practice" are somewhat vague. How is assessing "grasp of practice" different from assessing students' engagement in scientific practice? What features or observable behaviors should a teacher attend to as students are immersed in the practice of science? Additionally, translating this into the practicalities of evaluating student learning in an era of accountability is complex. What constitutes proficiency? How can student progress be documented? And How can such assessment be translated into grades?

23.6 Knowledge of Whole Science (KnOWS)

A third perspective, not inconsistent with that of Ford, is offered by Allchin (2011). He proposes assessing "knowledge of whole science" (KnOWS), moving away from declarative knowledge about NOS as the standard of understanding to *functional understanding* of science. Like Ford, Allchin emphasizes NOS understanding as a *critical* dimension of scientific literacy. He emphasizes, however, "a typical citizen, no matter how well informed, is simply unable to collect and evaluate all the evidence" needed to construct claims about complex scientific issues (2011, p. 521). That is, rather than preparing students to do what scientists do, he advocates for competence with interpreting the reliability of claims *in personal and social decision-making*.

Allchin argues that NOS instruction should engage students in problem-solving and decision-making through the context of rich contemporary and historical case studies. The benefits of such an approach are well documented in the literature—particularly when the goal is developing students' functional scientific literacy (Hodson 2009). The superlative goal from such efforts is to promote more robust and holistic understandings of the nature of science (NOS) that can facilitate students' democratic engagement of socioscientific issues (SSI), which are complex and contentious scientific matters that often entail moral and sociocultural dimensions (Khishfe 2012; Sadler et al. 2004; Wong et al. 2008).

For example, a case analysis approach provides students opportunities to inquire, evaluate, and interpret the veracity of scientific claims and actual scientists' work (Allchin 2011; Clough et al. 2010; Deng et al. 2011; Faria et al. 2012; Howe and Rudge 2005; Irwin 2000). Through such cases, students may be better able to reflectively, critically and contextually understand aspects of "science-in-the making" such as the tentative, subjective, methodological and evidentiary dimensions involved with the scientific enterprise (Allchin et al. 2014, p. 467). In this manner, such approaches might also be utilized to facilitate the development of declarative knowledge of NOS.

Yet, Allchin argues that teachers should evaluate students' understanding of NOS through their ability to make a well-informed analysis in the interest of making personal and social decisions, rather than what they can articulate about NOS.

> …learning will be indicated, not by agreement with prescribed statements, but by the degree, both in breadth and depth, to which a student is informed about the factors that shape the reliability of scientific claims (2011, p.528).

To this end, Allchin proposes six features to frame an appropriate instrument for assessing functional NOS knowledge: (1) *Authentic context;* students should demonstrate their NOS understanding in response to cases that actually occurred and may be encountered in real life (e.g., news reports, advertisements). (2) *Well-informed analysis;* instead of focusing on declaring specific NOS principles, assessments should focus on how well students analyze scientific claims using evidence and provisional contexts toward proper decision making. (3) *Adaptability to diagnostic, formative, or summative evaluation contexts;* assessment should be flexible enough to measure different types and levels of NOS competencies and be applied to different purposes. (4) *Adaptability to single and mass and to local and large-scale comparative use;* assessments should provide results that demonstrate validity across implementations of varying latitude. (5) *Adaptability to performance-based assessment;* assessments should evaluate and document students' competency throughout their learning process, not by a single "high-stake" test. (6) *Respect for relevant stakeholders;* the development, implementation, scoring system and outcomes of NOS assessments should practically consider the interests and intended goals of multiple NOS education stakeholders (e.g., students, teachers, administrators and policy makers, scientists, philosophers and sociologists of science).

While these guidelines offer a comprehensive assessment view (encompassing the development of research instruments and standardized assessments) they could also be useful for guiding the design of classroom assessments of NOS by teachers. Indeed, Allchin provides a prototype item modeled after those included on Advanced Placement (AP) exams that is open-response format:

> A female acquaintance of yours is just turning 40. Concerned about the possibility of breast cancer, she had planned to get a mammogram in the next few months, despite her fears about excessive radiation. She has heard that a major national task force now advises waiting until 50, yet finds reassurance in Women's Health magazine about still following the old guidelines. You both knew another woman who was diagnosed unexpectedly with breast cancer at age 43 and died last year. Your acquaintance is unsure how to interpret the apparently conflicting information and asks your help. What analysis of this reported change in scientific consensus would you provide to inform her decision? (2011, p. 520.)

This item addresses features of some research instruments that may be problematic for use by classroom teachers and reflects his view that, "…an effective instrument will *not* ask students "What is your view? Or "What would you do?" …an assessment must avoid values, ideology, and personal judgment" (2011, p. 529). This approach is explicitly intended to move away from previous research assessments that focus on learners' *views* or *beliefs* about NOS, to assessment of a flexibly operant NOS knowledge base and set of analytical abilities (Herman 2015). Allchin also identifies possible dimensions of reliability of science that might be scored in such a free response item; however, the scoring rubric is underdeveloped in terms of being classroom-ready for teachers to evaluate student work and translate those evaluations into a grade or score.

23.7 Discussion

Our review of the sparse literature on the subject of classroom NOS assessment raises many questions for both research and practice related to classroom assessment of students' understanding of NOS. In particular, it highlights the centrality of one's conception of what constitutes an understanding of NOS and purpose for teaching NOS in guiding assessment.

We note that despite a great deal of focus on understanding students' ideas about NOS and assessment of declarative knowledge of NOS in research instruments, declarative knowledge about NOS is not assumed to be the ultimate goal when teaching about the nature of science. For example, Driver et al. (1996) identify five distinct rationales for teaching students about the nature of science. These include: (1) a utilitarian argument that "understanding of the nature of science is necessary if people are to make sense of the science and manage the technological objects and processes they encounter in everyday life" (p.16); (2) a democratic argument wherein "understanding the nature of science is necessary if people are to make sense of socio-scientific issues and participate in the decision-making process" (p.18); (3) a cultural argument that views understanding the nature of science as "necessary in order to appreciate science as a major element of contemporary culture" (p.19); (4) a moral argument to help "develop awareness of the nature of science, in particular the norms of the scientific community, embodying moral commitments which are of general value" (p.19); and (5) a pedagogical argument that "understanding of the nature of science supports successful learning of science content" (p.20). In considering these rationales, it becomes clear that declarative knowledge about NOS is not itself an end, but rather a means to an end. Thus far, however, research has failed to establish a direct link between students' declarative knowledge of NOS and any of the above rationales or aims. Consequently, we believe that assessing students' understanding of aspects of NOS (as declarative knowledge) alone may be insufficient for classroom teachers to determine whether their NOS instruction has met its aim. That is, being able to articulate ideas about NOS doesn't necessarily mean that a student is able to make sense of scientific issues in the public forum or appreciate science as a part of his/her culture. As such, while probing learners' views of NOS may be an appropriate focus for the purposes of research and answering particular research questions, we argue that the focus of teachers' classroom assessment should extend beyond this.

Consistent with this, the notion of "grasp of practice" offered by Ford goes beyond simply possessing an understanding of NOS to using that understanding as a "reasoning resource" for engaging appropriately in scientific practices. In many ways, this meets the vision for K12 science described in recent reforms, and focuses on student engagement in doing science. However, the goal of science education is not merely for students to be able to practice science, but also to become a scientifically literate citizenry. Herein, Allchin's conceptualization of Knowledge of "Whole Science" both aligns with Ford's focus on constructing and critiquing claims and extends the utility of understanding NOS to the application of that knowledge to personal and social decision-making in authentic contexts.

The importance of the context in which NOS assessment tasks are situated has long been recognized (Hodson 2009). Leach et al. (2000) found students' responses to generalized questions (e.g., *Do scientific ideas change?*) are not a good predictor of how they respond to questions in specific contexts, nor across a wide range of contexts. While the three perspectives here suggest different contexts in which students' understanding of NOS might be assessed, these are not necessarily mutually exclusive. Clough (2006) argues that rich NOS teaching and learning requires scaffolding back and forth across a continuum of contexts that are decontextualized (i.e., devoid of science content), moderately contextualized (i.e., unified with scientific inquiry and content), and highly contextualized (i.e., embedded within historical and contemporary science examples clearly profiling the development of science ideas).

This latter point suggests that *all three perspectives* may serve to inform the design of classroom assessments for NOS in ways that support multiple instructional goals and aims. For example, "characterizing and measuring NOS understanding explicitly is necessary and helpful" (Ford 2008 p. 174). Eliciting students' ideas about NOS (declarative knowledge) would be an important first step toward achieving conceptual change (Clough 2006). Building on this, "a grasp of practice may offer students resources for working out the conceptual puzzles common to learning as conceptual change (Ford 2008, p. 174). Finally, assessing students' translation of their abilities as critiquers and constructors of science claims in the classroom to citizenship abilities, such as reacting to public claims, would require examination of knowledge of "whole science." We elaborate on these recommendations below and consider the role that science educators might play in this process.

23.8 Recommendations

While methods and approaches for assessing students' understanding of NOS for research purposes have long been debated, there has been very little discussion of, or investigation into, the methods and approaches for assessing students' understanding of NOS for classroom instructional purposes. Our chapter highlights the need for researchers to attend to and better understand *classroom assessment practices* when investigating teachers' NOS instruction, as well as to engage in the development and field-testing of high-quality *classroom assessment tools and strategies* for NOS. This latter point echoes a need for high-quality assessment tools and resources that has been emphasized more broadly in science education (Gearhart et al. 2006). As tools for both evaluating and informing instruction, NOS assessments could play an important role in achieving the broader goal of supporting effective instruction of NOS. Herein, we provide some recommendations for future research and assessment design, and professional development efforts to support classroom assessment of NOS.

23.9 Researching Teachers' Classroom Assessment of NOS

The framework of PCK has provided a useful lens for researchers to identify key gaps in teachers' knowledge of *what to assess* and *how* in relation to NOS (e.g., Hanuscin et al. 2010). We note, however, that while research has examined teachers' conceptions of NOS, researchers have not probed teachers' conceptions of what students should learn about NOS—a subtle, but important distinction, as one has direct relevance to the work of teaching, including assessment.

A potential framework for examining assessment of NOS more deeply is that of assessment literacy (Abell and Siegel 2011). This model takes into account not only knowledge of *what to assess* and *how* (which are part of teachers' PCK and knowledge of assessment) but also teachers' knowledge of assessment purposes and interpretation and action taking. Such a framework draws attention to dimensions of NOS instruction not previously explored, such as teachers' use of diagnostic, formative, summative, and metacognitive assessments; how they interpret the results of those assessments; and how that informs their subsequent NOS instruction.

Accordingly, a research agenda related to teachers' classroom NOS assessment should probe teachers' ideas about what constitutes "understanding NOS" as well as considering the range of assessment strategies (both formal and informal) teachers implement and their purpose in doing so. Given there are multiple purposes for assessment, research should explore the extent to which teachers use assessment data to diagnose students' misconceptions, provide feedback to students, or inform their teaching. Similarly, criteria by which teachers evaluate student understanding of NOS and translate that into grades merits examination. A richer understanding of teachers' current assessment knowledge and repertoire of practices would also yield important insights about their specific needs for assessment tools and resources.

23.10 Development of Classroom NOS Assessments

While the research described above may shed light on teachers' current practices and the assessment tools they have created, this does not negate the need for classroom-specific NOS assessments to be developed. Currently, there are few such tools and resources available. In a now out-of-print book for teachers, Bell (2008) includes a chapter on assessment of the nature of science, and argues that assessment of NOS is a necessary part of teaching NOS. In addition to several notebook exercises used for formative assessment, he suggests that "having students complete a concept map of their views of the nature of science or participating in an oral exam" (2008, p. 252) could be used as summative assessments. Several volumes of the *Uncovering Student Ideas in Science* by Page Keeley also include NOS-focused assessment probes. For example, *Is it a theory?* (Keeley 2014) is intended for use in formative assessment—eliciting students' ideas about theories and laws as forms of scientific knowledge. These assessment examples reflect a view of NOS as declarative knowledge, yet we know of no other published classroom assessment tools that reflect perspectives of NOS as "grasp of practice" or KNOWS.

Given the current lack of high-quality classroom NOS assessments, and teachers' struggles to devise their own, a design-based research approach (Confrey 2006) that pairs researchers and practitioners could help facilitate development of model assessment tools and resources for NOS. It is worth understanding how these might serve to inform and help teachers further develop their NOS instruction, as this has been suggested as a missing "feedback loop" in teaching and learning about NOS (Hanuscin et al. 2010). What we suggest is somewhat different from assessment development for the purposes of conducting action research (e.g., Akerson et al. 2010), or in which teachers adopt research instruments for classroom purposes (e.g., Bell 2008). Researchers can support the development of valid and reliable *classroom* assessment tools and tasks, as well as understand how these could be contextualized and implemented by teachers for different purposes.

23.11 Professional Development Efforts

Teachers' own understanding of NOS, of course, remains a perpetual concern as evident by continued research and indeed this very volume. Assessments that help elicit students' ideas about NOS can be important given role that students' prior conceptions play in the learning process; however, these will do little to improve student learning in cases where teachers lack the understanding of NOS and pedagogical strategies to respond to students' ideas with instruction (cf. Wahbeh and Abd-El-Khalick 2014). For this reason, any attempt to support teachers' assessment of NOS must be accompanied by professional development and learning about NOS and how to teach it. Indeed, professional development approaches that engage teachers in looking at student work have proven more effective than others in supporting teacher and student learning (cf. Heller et al. 2012). This suggests the long-overlooked matter of teachers' assessment of NOS may perhaps be the key to improving teachers' NOS instruction.

References

Abd-El-Khalick, F. (2014). The evolving landscape related to assessment of nature of science. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of research on science education* (2nd ed., pp. 621–650). Mahwah: Lawrence Erlbaum.

Abd-El-Khalick, F., Bell, R. L., & Lederman, N. G. (1998). The nature of science and instructional practice: Making the unnatural natural Inc. *Science Education, 82*, 417–436. https://doi.org/10.1002/(SICI)1098-237X(199807)82:4<417::AID-SCE1>3.0.CO;2-E.

Abell, S. K., & Siegel, M. A. (2011). Assessment literacy: What science teachers need to know and be able to do. In D. Corrigan, J. Dillon, & R. Gunstone (Eds.), *The professional knowledge base of science teaching* (pp. 205–221). Dordrecht: Springer Netherlands.

Akerson, V., Cullen, T., & Hanson, D. (2010). Experienced Teachers' strategies for assessing nature of science conceptions in the elementary classroom. *Journal of Science Teacher Education, 21*(6), 723–745.

Allchin, D. (2011). Evaluating knowledge of the nature of (whole) science. *Science Education, 95*(3), 518–542.

Allchin, D., Andersen, H. M., & Nielsen, K. (2014). Complementary approaches to teaching nature of science: Integrating student inquiry, historical cases, and contemporary cases in classroom practice. *Science Education, 98*(3), 461–486.

Aydin, S., Demirdogen, B., Muslu, N., & Hanuscin, D. (2013). Professional journals as a source of PCK for teaching nature of science: An examination of articles published in The Science Teacher (an NSTA journal), 1996-2010. *Journal of Science Teacher Education, 24*, 977–997.

Bartholomew, H., Osborne, J., & Ratcliffe, M. (2004). Teaching students "ideas-about-science": Five dimensions of effective practice. *Science Education, 88*(5), 655–682.

Bell, R. (2008). *Teaching the nature of science through process skills: Activities for grades 3–8*. Boston: Pearson.

Black, P., & Wiliam, D. (1998). Assessment and classroom learning. *Assessment in Education, 5*, 7–71.

Chen, S., Chang, W. H., Lieu, S. C., Kao, H. L., Huang, M. T., & Lin, S. F. (2013). Development of an empirically based questionnaire to investigate young students' ideas about nature of science. *Journal of Research in Science Teaching, 50*(4), 408–430. https://doi.org/10.1002/tea.21079.

Chen, S. (2006). Development of an instrument to assess views on nature of science and attitudes toward teaching science. *Science Education*, *90*(5), 803–819.

Chen, Y.-C., Hand, B., & Park, S. (2016). Examining elementary students' development of oral and written argumentation practices through argument-based inquiry. *Science & Education, 25*(3–4), 277–320. https://doi.org/10.1007/s11191-016-9811-0.

Cite, S., & Hanuscin, D. (2014). Professional journals as a source of information about teaching NOS: An examination of articles published in Science & Children, 1996–2010. *Science Education International, 25*(4), 396–416.

Clough, M. P. (2006). Learners' responses to the demands of conceptual change: Considerations for effective nature of science instruction. *Science Education, 15*(5), 463–494.

Clough, M. P., & Olson, J. K. (2008). Teaching and assessing the nature of science: An introduction. *Science & Education, 17*(2–3), 143–145. https://doi.org/10.1007/s11191-007-9083-9.

Clough, M. P., Herman, B. C., & Smith, J. A. R. (2010, January 14–16). *Seamlessly teaching science content and the nature of science*. Paper presented at the *Association for Science Teacher Education (ASTE) National Conference*, Sacramento, CA.

Confrey, J. (2006). The evolution of design studies as methodology. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 135–152). New York: Cambridge University Press.

Deng, F., Chen, D.-T., Tsai, C.-C., & Chai, C. S. (2011). Students' views of the nature of science: A critical review of research. *Science Education, 95*(6), 961–999. https://doi.org/10.1002/sce.20460.

Driver, R., Leach, J., Millar, R., & Scott, P. (1996). *Young people's images of science*. Buckingham: Open University Press.

Duschl, R. (2008). Science education in three-part harmony: Balancing conceptual, epistemic, and social learning goals. *Review of Research in Education, 32*(1), 268–291. https://doi.org/10.3102/0091732X07309371.

Duschl, R. A., & Grandy, R. (2012). Two views about explicitly teaching nature of science. *Science & Education, 22*(9), 2109–2139.

Elby, A., & Hammer, D. (2001). On the substance of a sophisticated epistemology. *Science Education, 85*(5), 554–567. https://doi.org/10.1002/sce.1023.

Faria, C., Pereira, G., & Chagas, I. (2012). D. Carlos de Bragança, a Pioneer of experimental marine oceanography: Filling the gap between formal and informal science education. *Science & Education, 21*(6), 813–826. https://doi.org/10.1007/s11191-010-9239-x.

Ford, M. (2008). "Grasp of practice" as a reasoning resource for inquiry and nature of science understanding. *Science and Education, 17*(2–3), 147–177. https://doi.org/10.1007/s11191-006-9045-7.

Gearhart, M., Nagashima, S., Pfotenhauer, J., Clark, S., Schwab, C., Vendlinski, T., Osmundson, E., Herman, J., & Bernbaum, D. J. (2006). Developing expertise with classroom assessment in K12 science: Learning to interpret student work. *Educational Assessment, 11*(3–4), 237–263.

Hanuscin, D. L. (2013). Critical incidents in the development of pedagogical content knowledge for teaching the nature of science: A prospective elementary Teacher's journey. *Journal of Science Teacher Education, 24*(6), 933–956. https://doi.org/10.1007/s10972-013-9341-4.

Hanuscin, D., Lee, M. H., & Akerson, V. L. (2010). Elementary teachers' pedagogical content knowledge for teaching the nature of science. *Science Education, 95*(1), 145–167.

Heller, J. I., Daehler, K. R., Wong, N., Shinohara, M., & Miratrix, L. W. (2012). Differential effects of three professional development models on teacher knowledge and student achievement in elementary science. *Journal of Research in Science Teaching, 49*(3), 333–362. https://doi.org/10.1002/tea.21004.

Herman, B. C. (2015). The influence of global warming science views and sociocultural factors on willingness to mitigate global warming. *Science Education, 99*(1), 1–38. https://doi.org/10.1002/sce.21136.

Herman, B. C., Clough, M. P., & Olson, J. K. (2013). Teachers' NOS implementation practices two to five years after having completed an intensive science education program. *Science Education, 97*(2), 271–309.

Hodson, D. (2009). *Teaching and learning about science: Language, theories, methods, history, traditions and values*. Boston: SensePublishers.

Howe, E. M., & Rudge, D. W. (2005). Recapitulating the history of sickle-cell Anemia research. *Science & Education, 14*(3–5), 423–441. https://doi.org/10.1007/s11191-004-1996-y.

Irwin, A. R. (2000). Historical case studies: Teaching the nature of science in context. *Science Education, 84*(1), 5–26. https://doi.org/10.1002/(SICI)1098-237X(200001)84:1<5::AID-SCE2>3.0.CO;2-0.

Jiménez-Aleixandre, M. P. (2014). Determinism and under determination in genetics: Implications for students' engagement in argumentation and epistemic practices. *Science & Education, 23*(2), 465–484. https://doi.org/10.1007/s11191-012-9561-6.

Keeley, P. (2014). Formative assessment probes: Is it a theory? Speaking the language of science. *Science and Children, 52*(1), 26–28.

Khishfe, R. (2012). Relationship between nature of science understandings and argumentation skills: A role for counterargument and contextual factors. *Journal of Research in Science Teaching, 49*(4), 489–514. https://doi.org/10.1002/tea.21012.

Leach, J., Millar, R., Ryder, J., & Séré, M.-G. (2000). Epistemological understanding in science learning: The consistency of representations across contexts. *Learning and Instruction, 10*(6), 497–527. https://doi.org/10.1016/S0959-4752(00)00013-X.

Lead States, N. G. S. S. (2013). *Next generation science standards: For states, by states*. Washington, DC: The National Academies Press.

Lederman, N. G., Schwartz, R. S., Abd-El-Khalick, F., & Bell, R. L. (2001). Pre-service teachers' understanding and teaching of nature of science: An intervention study. *Canadian Journal of Science, Mathematics and Technology Education, 1*(2), 135–160. https://doi.org/10.1080/14926150109556458.

Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., & Schwartz, R. (2002). Views of nature of science questionnaire: Toward valid and meaningful assessment of learner's conceptions of nature of science. *Journal of Research in Science Teaching, 39*(6), 497–521.

Loughran, J., Berry, A., Mulhall, P., & Gunstone, D. (2003). Teaching and testing about the nature of science problems in attempting to determine students' perceptions. *Asia-Pacific Forum on Science Learning and Teaching, 4*(1), 1–19.

McComas, W. F. (1996). Ten myths of science: Reexamining what we think we know about the nature of science. *School Science and Mathematics, 96*, 10–16. https://doi.org/10.1111/j.1949-8594.1996.tb10205.x.

McComas, W. F., & Olson, J. K. (1998). The nature of science in international science education standards documents. In W. F. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 41–52). Dordrecht: Kluwer.

Ozgelen, S., Yilmaz-Tuzun, O., & Hanuscin, D. L. (2013). Exploring the development of preservice science teachers' views on the nature of science in inquiry-based laboratory instruction. *Research in Science Education, 43*(4), 1551–1570. https://doi.org/10.1007/s11165-012-9321-2.

Rogoff, B. (2003). *The cultural nature of human development*. Oxford: Oxford University Press.

Rudolph, J. L. (2000). Reconsidering the "nature of science" as a curriculum component. *Journal of Curriculum Studies*, *32*(3), 403–419.

Roth, W., & Roychoudhury, A. (1993). The nature of scientific knowledge, knowing and learning: The perspectives of four physics students. *International Journal of Science Education, 15*(1), 27–44. https://doi.org/10.1080/0950069930150103.

Ryder, J., & Leach, J. (2008). Teaching about the epistemology of science in upper secondary schools: An analysis of teachers' classroom talk. *Science & Education, 17*(2–3), 289–315. https://doi.org/10.1007/s11191-006-9007-0.

Sadler, T. D., Chambers, F. W., & Zeidler, D. L. (2004). Student conceptualizations of the nature of science in response to a socioscientific issue. *International Journal of Science Education, 26*(4), 387–409. https://doi.org/10.1080/0950069032000119456.

Salter, I. Y., & Atkins, L. J. (2014). What students say versus what they do regarding scientific inquiry. *Science Education, 98*(1), 1–35. https://doi.org/10.1002/sce.21084.

Schwartz, R., & Lederman, N. (2008). What scientists say: Scientists' views of nature of science and relation to science context. *International Journal of Science Education, 30*(6), 727–771.

Schwartz, R. S., & Lederman, N. G. (2002). "It's the nature of the beast": The influence of knowledge and intentions on learning and teaching nature of science. *Journal of Research in Science Teaching*, *39*(3), 205–236.

Vygotsky, L. S. (1978). *Mind in society: The development of higher mental process* (M. Cole, V. John-Steiner, S. Scribner, & E. Souberman, Ed. and Trans.). Harvard University Press (original work published 1930–1935).

Wahbeh, N., & Abd-El-Khalick, F. (2014). Revisiting the translation of nature of science understandings into instructional practice: Teachers' nature of science pedagogical content knowledge. *International Journal of Science Education, 36*(3), 425–466. https://doi.org/10.1080/09500693.2013.786852.

Wong, S. L., Hodson, D., Kwan, J., & Yung, B. H. Y. (2008). Turning crisis into opportunity: Enhancing student–teachers' understanding of nature of science and scientific inquiry through a case study of the scientific research in severe acute respiratory syndrome. *International Journal of Science Education, 30*, 1417–1439.

Part IV
Teaching Aspects of the Nature of Science: Specific Instructional Strategies and Settings

Chapter 24
Using Core Science Ideas to Teach Aspects of Nature of Science in the Elementary Grades

Meredith A. Park Rogers, Ranu Roy, and Alexander Gerber

24.1 Introduction

From the early stages of learning science, students need to consider not just the facts of but also how scientists investigate and form explanations that have led to what is known as the disciplinary knowledge of science. Having students explore in tandem the content of science with the tools of science can support students with developing an understanding about *science as an enterprise*, or what is referred to as the *Nature of Science* (NOS) (Lederman 2007; McComas and Nouri 2016; NGSS Lead States 2013). Providing students with the opportunity to establish an understanding of NOS, while concurrently engaging with core disciplinary ideas of science and practices of science, can provide a foundation for successful science learning across the grade levels (Clough 2006; NGSS Lead States 2013).

The time afforded to science in schools, however, and especially at the elementary level, is often limited due to an emphasis in literacy and mathematics in grades K–5 (Blank 2013). Therefore, elementary teachers need to be strategic in how they approach their teaching of science to ensure they are providing their students with a comprehensive learning of the endeavor of science, while also working within time constraints of covering other subject areas (Akerson et al. 2014a). Contextualized teaching of NOS is one approach to addressing this need (Akerson et al. 2014b) but is not always an easy task for elementary teachers because of limited content knowledge and self-efficacy for teaching science (Appleton 2007). Research shows, however, teachers cannot expect students to make the necessary connections or form the necessary understandings about the enterprise of science on

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_24

their own (Lederman and Lederman 2014). Students need to be guided in how to explicitly reflect and discuss the nature of science along with the practice of doing science and the core disciplinary ideas of science (Akerson et al. 2014a; Khisfe and Abd- El- Khalick 2002). Therefore, teachers need to model how to do this for their students and provide consistent learning experiences for their students incorporate explicit and reflective learning of NOS with core disciplinary ideas of science (Akerson et al. 2014b).

The purpose of this chapter is to provide an example of how a teacher can approach this kind of reform-based teaching with their students. In the following pages, we provide a thorough description of one lesson for use with upper elementary students to develop their understanding of the tools and products of science. Suggestions are also provided throughout the lesson regarding content and instructional methods to support the teacher in this endeavor. These suggestions come as a result of many implementations of a similar activity with preservice teachers; as well as other activities used with classroom teachers in professional development settings. The approach is designed to help elementary students learn about NOS while simultaneously engaged in an activity about that explores the notion that gravity is a force and it acts similarly with all objects. More specifically, in this lesson students engage with practices of science that include (a) planning and carrying out investigations, (b) analyzing and interpreting data, and (c) constructing explanations (for science).

To support students learning about the role of NOS in engaging in science and understanding what gravity is, we employ Zembal-Saul et al.'s (2013) instructional framework for constructing an evidence-based explanation. This framework, which the authors have termed CER, involves the development of a *Claim* (the answer to the question being explored), *Evidence* (the patterns found in the data gathered that supports the claim), and *Reasoning* (the science principle or concept that provides justification for the evidence found and thus the claim). In the lesson below, the CER framework is used as an instructional strategy to help develop students understanding that science is empirically based; meaning through analysis of the data sometimes patterns can be found that stay consistent regardless of the context and these patterns can generate explanations for phenomenon, such as "Scientific Laws." In science a law is a way of knowing and explaining a pattern occurring in nature and often the relationships identified in the patterns are expressed in mathematical terms. Since this lesson is targeting the elementary grades, we will not go so far as to express the concept of gravity using the complex formula Newton developed. Instead, the content focus will remain on having elementary students understand that gravity is a type of force used to explain the attraction between Earth and other objects.

Title of Activity Which ball will hit the ground first?

Target Grade Level 3–5

NOS Subdomain Targeted

Tools and Products of Science
- Scientific knowledge is empirically based
- Formation of "Laws" in science

24.1.1 Explanation of Targeted Aspects of NOS (for the Teacher)

In science, much of what is known is based on observing repeatable patterns in nature. Forming explanations, and thus scientific knowledge, comes from identifying patterns and anomalies in these patterns. The role of evidence in supporting explanations is critical to the practice of science so that scientific knowledge is formed, accepted, and argued objectively rather than through personal opinion. The development of scientific laws and theories relies on the empirical nature of science and could be described as "products" of science. They are related but distinct types of knowledge created and used in science. Laws then are formed "from facts and explain and predict individual occurrences or instances" (McComas 2003, p. 146).

Many students have naïve understandings about scientific laws. Thus, this activity attempts to engage students in examining how laws are formed as they learn science content and collect empirical data. The purpose of the lesson is for students to consider pattern they find in data in order to develop knowledge claims that are generalizable. This lesson is intended to provide precursor understandings which will assist students progressing onto secondary science, where they will need to understand how laws are formed in science.

24.1.2 Subject-Matter Targeted (for the Teacher)

According to "*A Framework for K-12 Science Education*" (NRC 2012)

Disciplinary Core Idea:

Physical Science Core Idea—Motion & Stability: Forces and Interactions [PS2.B].

Cross-cutting Concept:

Patterns

Scientific Practices:

Planning and carrying out investigations
Analyzing and interpreting data
Constructing explanations (for science)

24.1.3 Learning Goals (for the Student)

- To form an understanding about the importance of adhering to repeatable patterns in data in order to provide empirically based, rather than opinion-based, conclusions in science.
- From analyzing patterns in data develop a generalization (i.e., laws) that describes the data collected.
- Apply the scientific knowledge of gravity as a force interacting equally on objects when reasoning about the patterns they see in their data.

Time Two class periods (~45 min a period) + 1–2 periods for an extension activity

24.1.4 Materials for Periods One and Two

- For each group of students:
- 2 balls of the same size, but different mass (e.g., ping pong ball, golf ball)
- A balance or electronic scale.
- A meter stick.
- 2 stop watches
- A roll of masking tape.
- For each student:
- Science notebooks or prepared data collection sheets—see step three for Period 1. Will also need for planning extension activity following the discussion held during Period 2.
- Pencil
- For teacher:
- 2 balls of the same size, but different mass and one that is larger (i.e., golf ball and ping pong ball)
- Poster paper for the “Museum Walk.”

24.1.4.1 Description of Activity

NOTE: *Specific instructions for the teacher of what to do or say to the students are in italics.*

Period 1

1. *Begin with showing students two balls of the same size but different masses.* Engage the students by asking*: Which ball do you think will hit the ground first?* For all to view, the teacher should list the various outcomes to this question that the students give. Be sure to ask students to explain the reason behind their prediction, so just choosing a ball is not a sufficient, but their reason for why they are selecting a particular ball is also important to note.
2. Organize the students into groups of four. Inform the students that *as a class we will now design an investigation to gather data that will help us assess our predictions about which ball will hit the ground first, but also try to formulate an explanation about the outcome.* Ask the students first; *if our goal is to generate an answer to this question collectively is it important for all groups to follow the same process for investigating—why or why not?* Take some time to talk through these responses because it is important for students to understand the need for following a similar protocol for comparison of results.
3. Provide each group two balls of the same size but different mass, a scale, two stopwatches, masking tape, and a meter stick. As a class talk through how an investigation should be designed to control for certain variables (i.e., dependent) when the mass of the two balls is different (i.e., independent variable). Ask, *what data should be gathered and how should we organize our data so we can easily compare it after?*

   Suggestion

   If the teacher is unsure about how to hold this discussion, or the teacher feels the students need more guidance in setting up the investigation, the following is one approach that could be used.

   - Have a data collection table premade and give a copy to each student group for recording rather than having them set up their own tables in their science notebooks. These sheets could be pasted into their notebooks later. On the table be sure to include places to record the mass of each ball and the time it takes (in seconds) for each ball to hit the ground when released at the same time from a height of two meters. Provide 3 to 4 columns for recording the time of different trials for each ball.
   - After explaining the data collection table and what to record, direct the students to a spot along the classroom wall where they can measure two meters up from the ground and mark it with tape. Starting from this height each time and perhaps 10 to 15 centimeters out from the wall, one of the group members will release the two balls at the same time. Two other members are responsible for recording the time it takes the balls to drop (one student assigned to each ball) using the two stop watches provided.
   - This task should be completed 3–4 times with another member of the team responsible for recording the times in the data chart for each drop.
   - It is important that all members of the group keep their roles for each trial in order to reduce variation in human error.

4. Once all of the data is collected have the students return to their group table and ask them to now *look across the numbers their group has recorded for each trial and for each ball. Using this information, can they generate a claim (an answer) to the question: Which ball hit the ground first?* Remind the students that they also need to pull out from their data table the *evidence (patterns in the data) that supports their claim as to which ball is hitting the ground first?*

   While the student groups are working on this task, the teacher should move from group to group asking questions such as, *"How is the data (time) you recorded for each ball similar or different?", "What trends/patterns do you notice in your data?, "What did you conclude from analyzing data across your different trials that supports you in making this claim?" "Why do you think it is important for scientists to respect their evidence, and not try to manipulate it, when doing science?"*

   Asking these types of questions is critical to supporting students in learning to formulate evidence-based explanations in science, but it also helps them to reflect and make explicit their understanding that scientific knowledge is formed through the use of empirically based methods of investigation (i.e., NOS).
5. If time remains in this first period, prepare for a museum walk for students to examine other groups' evidence-based claim statement. If there is not time to complete all of this museum walk in the first period, stop after the preparation of the chart and pick up with the museum walk at the start of the next day/class period.

   Directions for Museum Walk

   - Provide each group a piece of post-it/chart paper where they can duplicate their group's claim and supporting evidence that they wrote in their notebooks.
   - Label these charts A-? and post around the room for all to see.
   - Before releasing the students on the museum walk direct the students to *first draw a T-chart (similar/different) in your science notebooks so you can record the letter of each group poster in either the "same as" or "different than" column.* Tell them that *you should make this determination based on how the other group posters are similar or different to your own group's poster.* Further explain that *for group posters you note as having a different evidence-based claim than your own be sure to note in your chart what exactly the difference is so we can bring this up in the whole class discussion.*
   - Allow for enough time for all students to move around the room to read all other group's statements.

6. A whole class discussion about what they recorded in their T-charts about how other groups' explanations compared to their own group's explanation can take place in the next period.

Period 2

1. Begin with revisiting what they accomplished in the previous day's activity and where they left off. If there was no time for the museum walk in the last class begin there (see item 5 above for directions).

   If the museum walk was completed, then begin today's discussion with facilitating a whole class discussion about what they recorded in their T-charts about how other groups' explanations compared to their own group's explanation. Some guiding questions for this discussion are:

   - *What do you notice is the same about how your explanation compared to your peers? What is different? Why do you think these differences might be occurring?*
   - *Do you think the explanations you and your peers are beginning to generate model good science? In other words, are the claims grounded in the evidence and therefore, empirically based? Why or why not?*
   - *As scientists, why is it important for us to adhere to what the evidence is telling us when thinking about forming a claim to answer our question?*

   It is important to take the time here to connect their experience with gathering data, analyzing the data, and using the patterns found from their analysis to generate their claim, to the bigger picture of how this relates to the processes scientists follow when generating new knowledge in science. In other words, the students are not forming new scientific knowledge but they are experiencing through the practice of science the importance of evidence in supporting the formation of new knowledge. Thus, they are tangentially doing science as scientists would and are gaining first-hand experience regarding NOS. At this point, making this connection explicit to the students is critical as they move into thinking about the formation of Laws in science, as this will serve as the "Reasoning" component for their explanation.
2. Returning to the groups' evidence-based claims used in the museum walk, the teacher now leads a discussion to help the class come to a consensus about one claim statement the students believe best articulates what each group found in their data. Again, restate for the students: *Remember, our focus question was: Which ball hits the ground first*? *Which claim statement out of all the ones listed do we think best represents the class consensus to answer this question? Consider the patterns we noticed across all our data.* An example of claim statement might be:

   - CLAIM: When the two balls are released at the same time, they appear to be hitting the ground at the same time.
   - EVIDENCE: Comparing our collective evidence, we found each group had very little/if any difference in the time it took for each ball to reach the ground. This was consistent with each time trial recorded by each group.

3. Transitioning to the role of scientific laws as a way of explaining phenomenon, the teacher can begin with saying: *Now that we have our answer to our focus question and our evidence to support it, we need to know why the results we got*

make sense from a scientific standpoint. In other words, does anyone know about a scientific idea or concept that could be used to help us justify why our results make sense? If no, *well let's take a look at this video* (see Teacher Content Note below). *It describes a science idea called "Gravity." Perhaps after learning a little bit about what gravity is we can use this idea to help us better understand our results.*

Teacher Content Note

When released, the two balls appear to be dropping because they are attracted to Earth. However, Earth is also attracted to them—equally and so Earth is moving toward both balls at the same rate. The difference in mass between the two balls is very small compared to the difference in mass between Earth and the two balls. Therefore, the balls appear (to our eye) to come into contact with the ground (Earth) at the same time. See the following video for further details: https://ed.ted.com/lessons/jon-bergmann-how-to-think-about-gravity#review (Bergmann 2017).

Suggestion for Post Video/Reading Discussion

Gravity is a concept in science that is actually described by the "The Law of Universal Gravitation." This Law was developed by a famous scientist names Sir Isaac Newton. He formed this law using methods similar to what we did in our investigation—he observed something over and over and noted the pattern he was finding in his observations. From this he could generate a "rule" of sorts that helped to define what was going on consistently in his observations. Often these rules are represented in science in a mathematical way.

Do you think Newton would stop at testing his rule with just one experiment like we did? How could he know for sure that the pattern he was observing, the rule he was generating, would hold true for all different types of circumstances with objects falling? What do you think we could to test our claim then to see if what we are thinking holds for other situations?

4. From the conversation above, guide the students back to working in groups and in their science notebooks they need to devise a plan for testing if the claim the class developed holds true for other falling objects. In this extension activity, the groups can be testing items made of different materials, different size items, and items of different masses than the balls used before. They will need to be reminded about the need to keep other variables (height at which things are dropped, the role of each person, etc.) consistent so the only difference are the items themselves that are being dropped.
5. The extension activity could serve as an assessment for groups or students could conduct it individually. When comparing their results (claim and evidence) from the second experiment to the first experiment, does the rule hold? Does the law of universal gravitation, still apply as a justification for what they found in experiment two? These are the essential questions for students answer in order to show what they have learned about the content, practices, and nature of science over the course of this multi-day lesson. In addition, the following questions regarding the NOS ideas addressed in this lesson should be asked.

- What does it mean that science is empirically based and why is this important for the development of scientific knowledge?
- How is a law formed in science and what is its role in explaining phenomenon?

24.2 Conclusion

Learning about NOS is necessary for students to develop a more robust understanding of what is science, including the constructs and values inherent to the enterprise of science (Lederman 2007; McComas and Nouri 2016; Next Generation Science Standards [NGSS] Lead States 2013). For this to occur however, teachers must be exposed to learning opportunities that not only have them learning about the content and practices of science but also the Nature of Science [NOS], as it this component that relates specifically to the enterprise of science (Lederman 2007; Lederman and Lederman 2014). The purpose of this chapter was to provide a detailed description of how the teaching of NOS, alongside the teaching of content and practices of science, can complement each other and help to develop a more robust understanding of what is science, as described in science education reforms.

For elementary teachers in particular, thinking about how to combine all of these aspects and contextualize them in an ambitious learning experience for their students can be daunting. Considering the example provided in this chapter, and with the inclusion of the CER framework as a means for guiding students to develop explanations in science, hopefully teachers can begin to feel less overwhelmed and willing to try this strategy for contextualized teaching of NOS.

References

Akerson, V. L., Weiland, I., Nargund-Joshi, V., & Pongsanon, K. (2014a). Becoming and elementary teacher of nature of science: Lessons learned for teaching elementary science. In M. Dias, C. J. Eick, & L. Brantley-Dias (Eds.), *Science teacher educators as K-12 teachers: Practicing what we teach* (pp. 71–88). Dordrecht: Springer.

Akerson, V. L., Weiland, I., Park Rogers, M., Pongsanon, K., & Bilican, K. (2014b). Exploring elementary science methods course contexts to improve pre-service teachers' NOS of science conceptions and understanding of NOS teaching strategies. *EURASIA Journal of Mathematics, Science & Technology Education, 10*(5), 219–236.

Appleton, K. (2007). Elementary science teaching. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 493–535). Mahwah: Lawrence Erlbaum Associates, Inc., Publishers.

Bergmann, J. (2017). *How to think about gravity*. TEDEd: Lessons worth sharing. Retrieved July 14, 2017, from: https://ed.ted.com/lessons/jon-bergmann-how-to-think-about-gravity#review

Blank, R. K. (2013). Science instructional time is declining in elementary schools: What are the implications for student achievement and closing the gap. *Science Education, 97*(6), 830–847.

Clough, M. P. (2006). Learners' responses to the demands of conceptual change: Considerations for effective nature of science instruction. *Science and Education, 15*, 463–494. https://doi.org/10.1007/s11191-005-4846-7.

Khisfe, R., & Abd- El- Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth graders' views of nature of science. *Journal of Research in Science Teaching, 39*, 551–578.

Lederman, N. G. (2007). Nature of science: Past, present, and future. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 831–879). Mahwah: Lawrence Erlbaum Associates,, Publishers.

Lederman, N., & Lederman, J. (2014). Research on teaching and learning of nature of science. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of research on science education* (Vol. 2, pp. 600–620). New York: Routledge, of Taylor and Francis Group.

McComas, W. F. (2003). A textbook case of the nature of science: Laws and theories in the science of biology. *International Journal of Science and Mathematics Education, 1*, 141–155.

McComas, W. F., & Nouri, N. (2016). The nature of science and next generation science standards: Analysis and critique. *Journal of Science Teacher Education, 27*, 555–576.

National Research Council [NRC]. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: The National Academies Press. https://doi.org/10.17226/13165.

NGSS Lead States. (2013). *Next generation science standards: For states, by states (Appendix H: Understanding the scientific enterprise: The nature of science in the next generation science standards).* Retrieved April 5, 2017, from: http://www.nextgenscience.org/sites/default/files/Appendix%20H%20-%20The%20Nature%20of%20Science%20in%20the%20Next%20Generation%20Science%20Standards%204.15.13.pdf

Zembal-Saul, C., McNeill, K. L., & Hershberger, K. (2013). *What's your evidence: Engaging K-5 students in constructing explanations in science*. Boston: Pearson.

Chapter 25
Improving Nature of Science Instruction in Elementary Classrooms with Modified Trade Books and Educative Curriculum Materials

Jeanne L. Brunner and Fouad Abd-El-Khalick

25.1 Introduction

This chapter describes a strategy for teaching about nature of science (NOS) in elementary grades through read-alouds with science trade books that have been modified to include explicit references to NOS. Teaching NOS has historically been difficult for teachers across grade levels. Research shows that even secondary teachers with a strong science background, an informed understanding of NOS, and the desire to teach NOS still struggle with effectively teaching NOS in their classrooms (Wahbeh and Abd-El-Khalick 2014). This issue is compounded for instructors at the elementary level because these teachers typically do not have adequate, let alone robust, science content knowledge and are not science specialists (Banilower et al. 2013). Still, it is especially important that NOS is addressed in elementary grades because by the time students reach the older grades, they will already have developed naïve NOS views (see Abd-El-Khalick and Lederman 2000; Lederman 1992; and Lederman and Lederman 2014 for reviews). In the absence of explicit NOS instruction, naive conceptions of NOS are learned incidentally through representations of NOS in textbooks (Abd-El-Khalick et al. 2008) and trade books (Brunner and Abd-El-Khalick 2017), language use in science classes (Lemke 1990), and even popular media (Aikenhead 1988; Walls 2012). Thus, there is a need for strategies

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_25

that help elementary teachers develop more informed views of NOS, as well as supporting them in implementing effective NOS teaching practices.

Unlike previous strategies involving lengthy and intensive professional development (PD) (e.g., Akerson and Hanuscin 2007; Lederman and Lederman 2004), the strategy outlined here relies on affecting practice through interactions with educative curriculum materials that address both teacher content knowledge and teaching practice. Traditional curriculum materials are designed to support teachers' pedagogical decisions—that is, how they enact the curriculum. *Educative* curriculum materials also support teachers' pedagogical decisions but have the additional goal of supporting their development of the content knowledge as well (Ball and Cohen 1996; Davis and Krajcik 2005). Thus, the materials described here support the teaching of NOS while also helping teachers develop more informed NOS views. Research has shown that NOS instruction must be explicit and reflective—that is, it must be specifically planned for, as well as reinforced with structured opportunities for student reflection (Abd-El-Khalick and Lederman 2000; Khishfe and Abd-El-Khalick 2002). Teachers often cite the lack of effective, NOS-specific instructional resources as a challenge even for those who would like to include this content in instruction (Wahbeh and Abd-El-Khalick 2014). Here, we address this lack of resources by discussing a plan to modify existing curriculum materials to support explicit and reflective teaching practices for NOS concepts.

The strategy is aimed at assisting practicing teachers, and is intended to be compatible with the realities of elementary classrooms, including aligning with typical teaching practices. Let us start with the notion that many elementary teachers incorporate trade books in their science instruction (Banilower et al. 2013) in a variety of ways, including reading them aloud during whole class instruction and guiding students through questions and discussions. Using trade books is beneficial because they allow teachers to approach science teaching in a way that is interesting and accessible to young children (Daisey 1994) and does not rely extensively on the teachers' own knowledge of science. Additionally, such use aligns with the strengths of most elementary teachers, who commonly specialize in reading instruction more so than in science (Banilower et al. 2013). In addition, reading instruction often takes up a large portion of their instructional time due to pressures from high stakes standardized testing. In particular, the recent adoption of the *Common Core State Standards* (National Governors Association Center for Best Practices & Council of Chief State School Officers 2010) mandates the use of informational and non-fiction texts in English Language Arts instruction. One common method that elementary teachers use to incorporate informational texts into instruction is teacher-led read-alouds. Thus, incorporating read-alouds into science instruction has multiple benefits: it is a familiar practice, draws on teachers' instructional strengths, and allows teachers to increase students' interactions with informational text by situating it within science content areas.

In the remainder of this chapter, we present a strategy for improving teaching and learning of NOS through the use of educative curriculum materials combined with science trade books that have been modified to explicitly and reflectively address elementary age-appropriate aspects of NOS. One major benefit of this strategy is that it is easily scaled throughout a school or district because it does not rely on outside professional development, but rather on materials that support explicit and reflective NOS instruction. These materials can be developed and used by teachers who hold informed views of NOS and are able to identify NOS ideas in trade books and then shared with those who are still developing their views. In addition to practicing teachers, this strategy also may be used with preservice teachers in elementary science methods courses that address NOS. Instructors could present this as a method for incorporating NOS instruction using existing science curriculum materials. Throughout this chapter, we will simply refer to teachers implementing this strategy, although our intent is to include preservice teachers as well.

We provide multiple examples here from our work with teachers reading aloud the book *Come See the Earth Turn: The Story of Léon Foucault* (Mortensen 2010). This book is one of three about Earth and space science that we used in our research on improving the teaching of NOS with elementary teachers (Brunner 2016). The book discusses the discovery by Léon Foucault (referred to simply as Léon in the examples) that the Earth rotates on its axis. Although we use this book as an example, our approach may be used with other trade books and science topics.

With this book, we focus on three aspects of NOS, namely, the: empirical NOS, which speaks to the notion that all scientific claims are based on or derive from empirical evidence; creative NOS, which highlights the role of creativity in both devising methods of investigation and in generating scientific explanations; and inferential NOS, which addresses the difference between observation and inference. These aspects are consistent with the NOS framework presented throughout this volume. We focused specifically on the three because there is evidence that elementary students are capable of developing informed views of these aspects (e.g., Akerson and Abd-El-Khalick 2005; Akerson et al. 2014; Lederman and Lederman 2004); however, it is important to note that our approach may be used to address various other NOS aspects.

25.2 The Strategy

The strategy relies on the use of two types of curriculum resources: trade books that are modified to explicitly/reflectively address NOS concepts in an informed way and accompanying educative curriculum materials, which support teachers in using the modified trade books effectively. Using educative curriculum materials is important because most practicing teachers do not have informed views of NOS. Our research shows that teachers who use these materials both improve their teaching of NOS, as well as their understanding of NOS (Brunner 2016). In the following sections, we first discuss the selection and modification of science trade books to be used in NOS instruction, and then follow with a description of the development of materials to be used with these trade books.

25.2.1 Selecting and Modifying Science Trade Books

The strategy relies on first selecting trade books that contain high quality science content and the potential to address NOS. Teachers may find listings provided by professional organizations, such as the Outstanding Science Trade Books by the National Science Teacher Association and Book Council (http://www.nsta.org/publications/ostb/) to be helpful resources for identifying trade books that contain high quality science content. The latter list contains literature that has been selected to support teachers in addressing the expectations of the NGSS (NGSS Lead States 2013). Our exemplar book, *Come See the Earth Turn* (Mortensen 2010) was included on the list for books published in 2010. We have also identified appropriate books through teacher recommendations, because many teachers incorporate read-alouds into their current science instruction. The strategy discussed here does not require teachers to abandon their favorite books. Instead, it may be used with books that teachers already use as long as they address the desired science concepts.

Books must also have the potential to address NOS. As they are originally written, most trade books do not adequately address NOS concepts (e.g., Abd-El-Khalick 2002; Brunner and Abd-El-Khalick 2017; Ford 2006; Kelly, 2018; Zarnowski and Turkel 2013). However, books that include descriptions of people doing science provide the opportunities for addressing NOS because they tend to show science as a process instead of as a collection of facts (Brunner and Abd-El-Khalick 2017; Zarnowski and Turkel 2013). Appropriate books may be narratives that tell the story of a scientist (such as our example book *Come See the Earth Turn* (Mortensen 2010)) or non-narrative books that include a description of scientists' work (e.g., *Galaxies, Galaxies!* by popular children's author Gail Gibbons (2007)). After selection, the books must be modified to include informed messages about NOS before they can be effectively used for explicit/reflective NOS instruction. The modification process can be discussed in two steps that can be used as a guide for teachers and collaborating researchers to modify any appropriate science trade book.

First, we read through a book and identified text that addressed targeted aspects of NOS, even though that may not have been the goal of the author. Teachers may find it helpful to first produce a list of criteria for content that aligns with specific NOS aspects. A good starting point for this list would be the NOS appendix in the NGSS (NGSS Lead States 2013). As an example, in our own work we looked for references to the creative NOS that involved scientists developing new technology or methods, modifying existing technology for an innovative use, or generating explanations from data. Next, we labeled each instance as treating a NOS aspect in an informed or naïve manner (albeit in our work, most of the identified instances were naïve). We also identified "missed opportunities," or places in the text where NOS concepts could have been seamlessly connected with the narrative but were not included.

Once these instances were identified, we modified the text in the trade books in two ways: (1) Minor modifications, which entailed changing a few words or phrases in the narrative, and (2) Major modifications, which entailed adding some substantial text and/or other elements (e.g., questions, reflective prompts) into the narrative. Teachers should be aware of the implications of modifying an author's creative product. In our own work, we kept as much of the author's own words as possible so that the storyline and aesthetic attributes of the work was not significantly altered. Additionally, modified trade books should not be reproduced and sold as a replacement to purchasing original materials, as this would violate U.S. copyright laws. If students are allowed to read these books on their own, teachers may want to have a discussion about how and why the changes were made. This provides an additional opportunity to explicitly discuss the targeted aspects of NOS. It can also be connected to English Language Arts topics by discussing how an author's purpose affects their writing (i.e., most authors intend to focus on content relevant to specific science topics and not NOS, which leads to the need to modify books used for NOS instruction).

Table 25.1 illustrates examples of both minor and major modifications from *Come See the Earth Turn*. There are two minor modifications. First, we changed the word "saw" to "observed" in the first paragraph to more clearly highlight the practice of observation in science, which is later contrasted with drawing inferences. Second, we changed "proved" to "provide evidence" in the second paragraph. The term "prove"—more appropriately used in mathematics—implies that evidence can be used to irrefutably establish a claim to scientific knowledge as absolute or true, which is a naïve treatment of the tentative NOS. By removing this term and highlighting the role of evidence in providing support for claims to scientific knowledge, we embedded a more informed reference to the empirical and tentative NOS.

The major modification, at the end of the first paragraph, is more nuanced. The original text implies that the act of seeing the lathe move immediately led to an

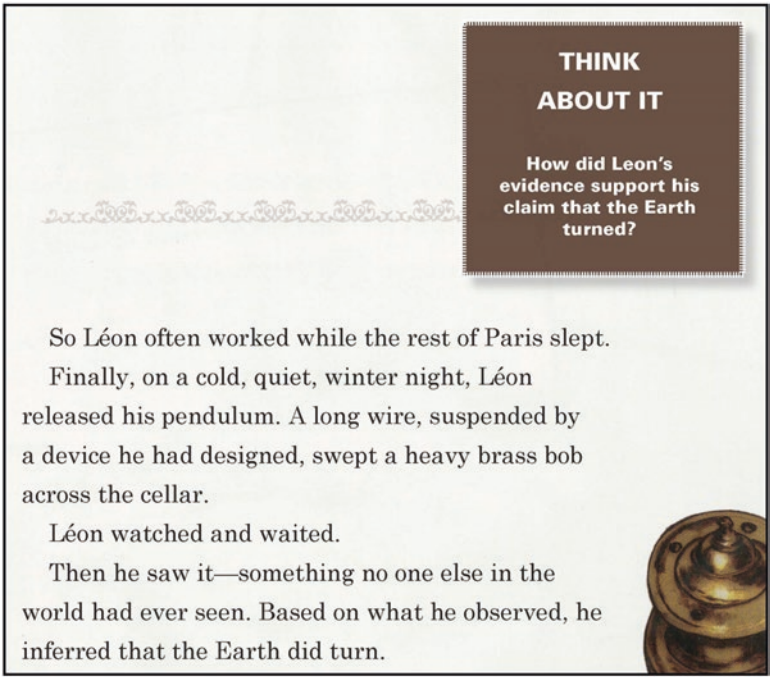
Table 25.1 Example of unmodified and modified text from *Come See the Earth Turn*

Unmodified text	Modified text
Then, one day, Léon made a startling discovery in his laboratory. He had clamped a steel rod into a lathe, a machine that allowed him to spin and shape objects. In moving the machine, Léon accidentally twanged the tip of the rod, setting it wiggling from side to side. Léon slowly turned the machine's crank to start the rod spinning. To his amazement, he saw that even though the rod began to spin, the tip kept wiggling side to side, independently from the spinning motion. At that moment, Léon understood how to answer a question that had baffled scientists for centuries: how can science prove that the earth spins on its axis? (Mortensen 2010)	Then, one day, Léon made a startling discovery in his laboratory. He had clamped a steel rod into a lathe, a machine that allowed him to spin and shape objects. In moving the machine, Léon accidentally twanged the tip of the rod, setting it wiggling from side to side. Léon slowly turned the machine's crank to start the rod spinning. To his amazement, he **observed** that even though the rod began to spin, the tip kept wiggling side to side, independently from the spinning motion. **Based on these observations, he inferred that this was similar to how the earth spins on its axis**. At that moment, Léon understood how to answer a question that had baffled scientists for centuries: how can science **provide evidence** that the earth spins on its axis?

Modifications are indicated in bold

understanding of how the Earth moved. This is not a conceptual leap that most observers would make. Instead, after observing the lathe, Léon had to infer that the lathe was somehow similar to the Earth, and only then could he understand how the movement of the lathe modeled that of the Earth. The modified text more clearly differentiates the practice of observing the lathe from the act of drawing an inference from this observation. It is important to note that in both of these modifications, the representation of NOS has perhaps lost some of its sophisticated philosophical treatment. However, this was done purposefully so that it is more easily accessible to elementary students who are just beginning to explore these ideas.

In addition to modifying the text, we also embedded reflective prompts and questions into the text. As noted above, research has shown that the most effective NOS teaching is explicit *and* reflective. Teachers can use embedded reflective questions to highlight the connection between the text and NOS concepts, as well as encourage young readers to consider their pre-existing views and how the modified text might challenge these views. This is a procedure that is most likely familiar to elementary teachers, as they regularly plan questioning opportunities during read-alouds. Teachers may want to link these questions to modifications that were made in the text, as these provide opportunities to address specific NOS content. Figure 25.1 provides an example of a reflective prompt, which we labeled "Think



THINK ABOUT IT

How did Leon's evidence support his claim that the Earth turned?

So Léon often worked while the rest of Paris slept.

Finally, on a cold, quiet, winter night, Léon released his pendulum. A long wire, suspended by a device he had designed, swept a heavy brass bob across the cellar.

Léon watched and waited.

Then he saw it—something no one else in the world had ever seen. Based on what he observed, he inferred that the Earth did turn.

Fig. 25.1 Example of a reflective question from *Come See the Earth Turn*

About It.” This question addressed the empirical NOS by guiding readers to consider how Léon used evidence in supporting his scientific claim that the Earth turned on its axis.

It is important to note that we digitally manipulated the texts to seamlessly integrate our modifications and reflective prompts with minimal interruption to the narrative. The process started by creating a digital copy of the narrative and, then, inserting our textual elements. If teachers do not have access to the resources to perform these modifications digitally, they may simply include the modified text on sticky notes inserted into the book in the appropriate place. Alternatively, if teachers own copies of the book, they may write the modifications directly into the text. Also, our modifications were intentionally calibrated and measured to ensure that we do not increase the reading difficulty for young learners. Practicing teachers have a very good sense of the reading abilities of their students and should be able to address this requirement without recourse to specific reading measures and formulas.

25.2.2 Developing the Educative Curriculum Materials

The previous section is predicated on the assumption that teachers using the trade books will have an informed understanding of NOS, and therefore will be able to identify and modify the trade books. However, this is not always the case, as many teachers hold less-than-desirable views of NOS (Abd-El-Khalick and Lederman 2000; Lederman 1992; Lederman and Lederman 2014). Therefore, our strategy also incorporates the development of educative curriculum materials, in the form of a teacher’s guide, to support teachers who need it. The teacher’s guide assists teachers in effectively using the trade books during read-alouds and contains multiple educative features to support teachers in developing accurate views of NOS. In elementary settings, this teacher’s guide may be designed by a lead science teacher or district curriculum designer who has informed views of NOS and shared with other teachers with more limited views. Additionally, preservice teachers who develop these materials in their methods courses may share them with their cooperating teachers during practicum or colleagues after graduation.

Although frequently used in educational settings, trade books are typically not specifically designed as teaching tools. As such, different teachers may use the same trade book in different ways. For example, it is possible to read one book aloud to students and focus on the science content or, alternatively, use it to highlight important concepts in reading. An educative teacher’s guide for science instruction should focus only on the NOS concepts targeted in the texts, thus highlighting NOS content for teachers who may not identify it on their own. This is not intended to limit the teachers from including any reading instruction into their read-aloud sessions, but instead to provide support in the NOS domain, where teachers usually struggle.

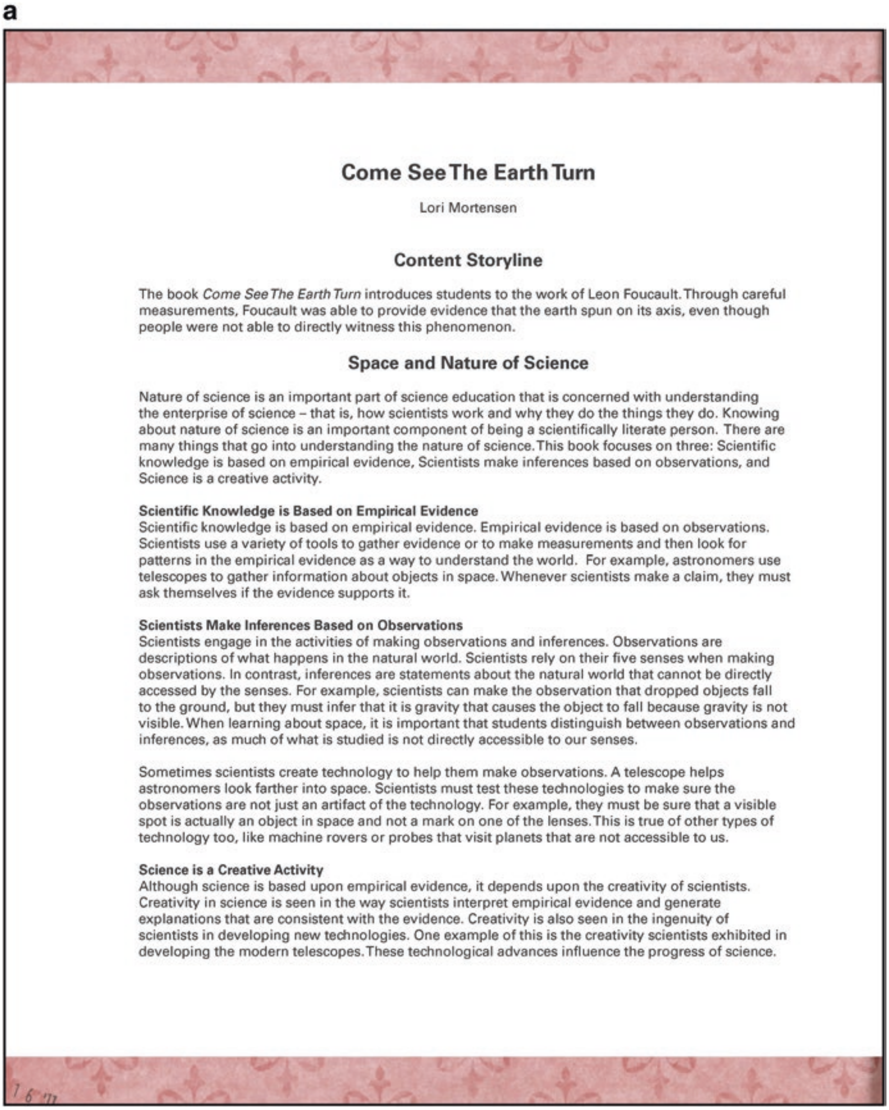
In the model teacher’s guide, we have developed there are five educative features. The guides we developed are similar to commercially produced teacher’s guides in their format: they contain an introduction and a learning section. The introduction contains free-standing information that relates to the book as a whole. The learning section consists of a scanned and minimized version of a trade book with wide margins into which we outlaid our educative elements. This increases ease of use, as the educative elements are spatially close to the relevant text. Similar to the modified trade books, the example provided here is an idealized version and every teacher may not have the resources to produce a teacher's guide in this manner. An alternative format may include a printout listing page numbers linked to the educative feature that relate to the content on that page.

Figures 25.2 illustrates several educative features included in the teacher's guide for *Come See the Earth Turn* (Mortensen 2010). These features addressed either general pedagogical content knowledge, pedagogical content knowledge for NOS, or NOS content knowledge (see Table 25.2 for a summary of these features). Including these elements supports teachers in developing their own views of NOS (the components addressing NOS content knowledge) and effectively teach NOS (general pedagogical content knowledge and pedagogical content knowledge for NOS).

In the introduction to the teacher's guide, we included a content storyline that provided a description of the book. Teachers may use this description to decide how this book would fit in a sequence of other trade books and/or within a broader inquiry unit. Thus, this feature addressed general pedagogical content knowledge. We also included a description of how the NOS content in the trade book could be connected with the NGSS (NGSS Lead States 2013) and the *Common Core State Standards for English Language Arts* (National Governors Association Center for Best Practices & Council of Chief State School Officers 2010). The purpose of these connections was to provide a rationale for why teaching NOS is important and how it can be done in alignment with other teaching goals, addressing pedagogical content knowledge for NOS. This is particularly important, as elementary teachers are already pressured to limit science instruction in favor of increasing English Language Arts instruction. By describing the connections, teachers are more likely to see the alignment between the content areas and associate their ability and effort to provide quality science instruction with meeting English Language Arts standards.

The third educative feature, also found in the introduction of the guide, was a description of each of the targeted NOS aspects, which provided teachers with a basic introduction to the NOS concepts (i.e., it highlighted NOS content knowledge). These descriptions were intended to introduce a NOS aspect in a few sentences and provide a general example associated with the aspect. In essence, this was meant to prime the teachers for recognizing the NOS content throughout the modified text. A fourth educative feature, NOS content boxes, expanded on these initial descriptions of various NOS aspects throughout the text. The content boxes contained information that related the reflective questions embedded within the text to specific NOS concepts.

To further support teachers in generating a rich discussion around NOS concepts, we included additional discussion questions in the teacher's guide. This fifth educative feature focused on extrapolating the concepts from the specific text to scientific practices in general. We provided possible student answers as a way to address



Come See The Earth Turn

Lori Mortensen

Content Storyline

The book *Come See The Earth Turn* introduces students to the work of Leon Foucault. Through careful measurements, Foucault was able to provide evidence that the earth spun on its axis, even though people were not able to directly witness this phenomenon.

Space and Nature of Science

Nature of science is an important part of science education that is concerned with understanding the enterprise of science – that is, how scientists work and why they do the things they do. Knowing about nature of science is an important component of being a scientifically literate person. There are many things that go into understanding the nature of science. This book focuses on three: Scientific knowledge is based on empirical evidence, Scientists make inferences based on observations, and Science is a creative activity.

Scientific Knowledge is Based on Empirical Evidence
Scientific knowledge is based on empirical evidence. Empirical evidence is based on observations. Scientists use a variety of tools to gather evidence or to make measurements and then look for patterns in the empirical evidence as a way to understand the world. For example, astronomers use telescopes to gather information about objects in space. Whenever scientists make a claim, they must ask themselves if the evidence supports it.

Scientists Make Inferences Based on Observations
Scientists engage in the activities of making observations and inferences. Observations are descriptions of what happens in the natural world. Scientists rely on their five senses when making observations. In contrast, inferences are statements about the natural world that cannot be directly accessed by the senses. For example, scientists can make the observation that dropped objects fall to the ground, but they must infer that it is gravity that causes the object to fall because gravity is not visible. When learning about space, it is important that students distinguish between observations and inferences, as much of what is studied is not directly accessible to our senses.

Sometimes scientists create technology to help them make observations. A telescope helps astronomers look farther into space. Scientists must test these technologies to make sure the observations are not just an artifact of the technology. For example, they must be sure that a visible spot is actually an object in space and not a mark on one of the lenses. This is true of other types of technology too, like machine rovers or probes that visit planets that are not accessible to us.

Science is a Creative Activity
Although science is based upon empirical evidence, it depends upon the creativity of scientists. Creativity in science is seen in the way scientists interpret empirical evidence and generate explanations that are consistent with the evidence. Creativity is also seen in the ingenuity of scientists in developing new technologies. One example of this is the creativity scientists exhibited in developing the modern telescopes. These technological advances influence the progress of science.

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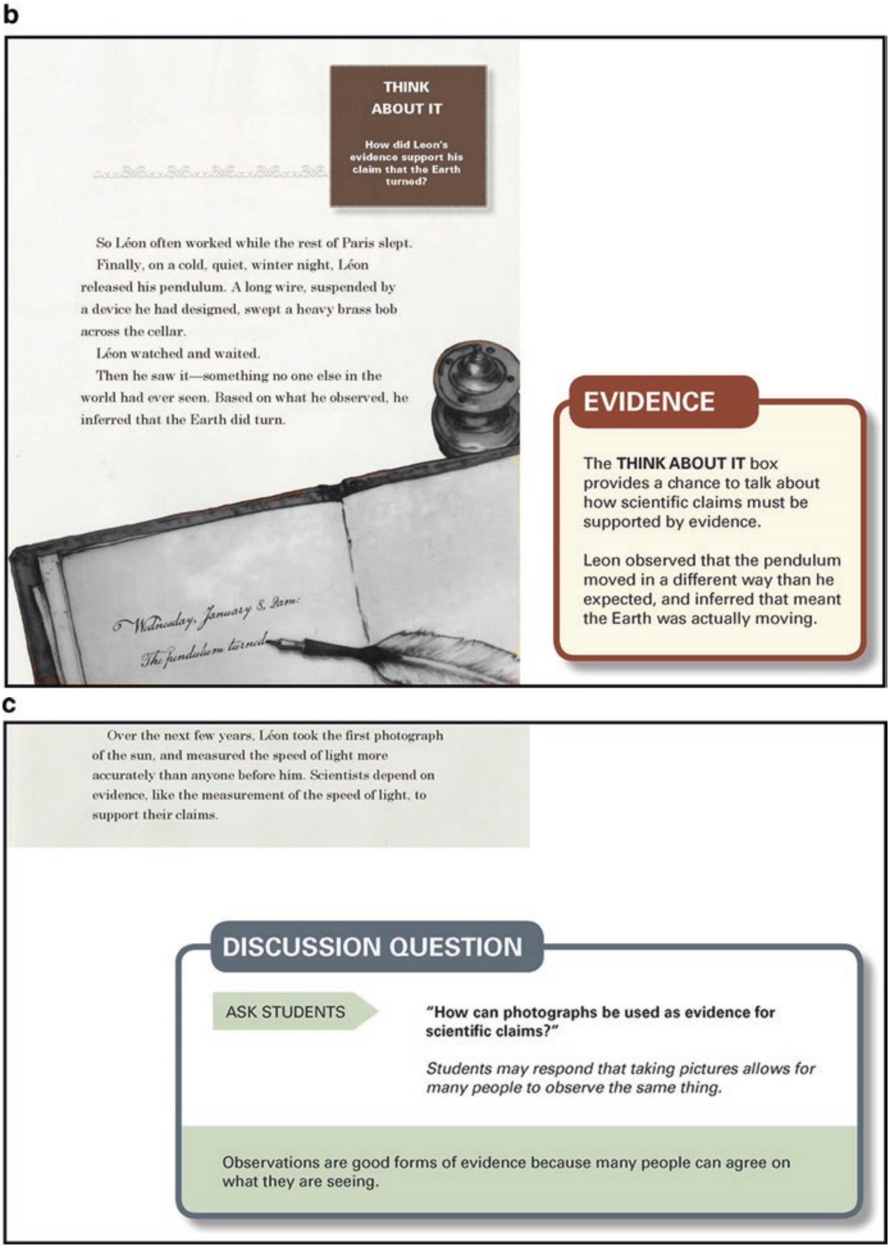
Fig. 25.2 (**a**) Two educative features in the introduction of *Come See the Earth Turn's* teacher guide: the content storyline and descriptions of the three targeted NOS aspects. (**b**) A content box provides teachers with more information about the NOS aspect that the reflective question addresses. (**c**) The discussion question includes a possible student answer, as well as a description of how it connects with NOS concepts



THINK ABOUT IT

How did Leon's evidence support his claim that the Earth turned?

So Léon often worked while the rest of Paris slept.

Finally, on a cold, quiet, winter night, Léon released his pendulum. A long wire, suspended by a device he had designed, swept a heavy brass bob across the cellar.

Léon watched and waited.

Then he saw it—something no one else in the world had ever seen. Based on what he observed, he inferred that the Earth did turn.

EVIDENCE

The **THINK ABOUT IT** box provides a chance to talk about how scientific claims must be supported by evidence.

Leon observed that the pendulum moved in a different way than he expected, and inferred that meant the Earth was actually moving.

Over the next few years, Léon took the first photograph of the sun, and measured the speed of light more accurately than anyone before him. Scientists depend on evidence, like the measurement of the speed of light, to support their claims.

DISCUSSION QUESTION

ASK STUDENTS

"How can photographs be used as evidence for scientific claims?"

Students may respond that taking pictures allows for many people to observe the same thing.

Observations are good forms of evidence because many people can agree on what they are seeing.

Fig. 25.2 (continued)

Table 25.2 Purpose and description of educative features

Educative feature	Purpose	Description	Location
Content storyline	General PCK[a]	A short description of how this lesson fits within the overall unit to help teachers contextualize the specific lesson and provide coherence	Introduction
Description of the relevant aspects of NOS	NOS-CK	Description of the role of the empirical, inferential, and creative NOS as these pertain both in science in general and to the content of the trade book	Introduction
Connections between NOS and the NGSS	PCK for NOS	Description of NOS in the NGSS and how this pertains to the content of the trade book	Introduction
Content boxes	NOS-CK	Highlight of important NOS content in the trade books	Margins of the learning section
Discussion questions	PCK for NOS	Questions meant to relate NOS content in the trade books to students' experiences. These questions also provide opportunities for students to reflect on the NOS content	Margins of the learning section

[a] *PCK* pedagogical content knowledge

student naïve conceptions and guide teachers in what would be more desirable responses. Additionally, we described the relevant NOS concepts addressed in the discussion question.

25.3 Implementing the Strategy in the Classroom

We have modified and created supporting materials for three trade books, which were used in read-alouds by eight teachers (Brunner 2016). We compared these read-alouds with ones from books that had not been modified. Regardless of their initial views of NOS, every teacher gained more appropriate NOS knowledge and incorporated more informed references of NOS through the use of the modified materials. Students were also impacted: they engaged in more explicit discussions around NOS as well as showed evidence of changing to more informed views of NOS. These results indicate the effectiveness of this strategy at supporting NOS instruction, as well as supporting the development of more informed views of NOS.

One of the benefits of educative curriculum materials is that they make the rationale for the specific design of a unit or activity transparent (Ball and Cohen 1996). This transparency allows teachers to make informed decisions about how they will actually implement the unit or activity in their own classrooms. Thus, the effectiveness of educative curriculum materials does not rely on teachers following a recipe-like procedure, but instead draws on the assembly of existing teacher knowledge (e.g., of their students) with pedagogical supports for unknown content (i.e., NOS concepts).

In practice, teachers used the modified trade books and teacher's guides differently. One relatively more effective strategy included highlighting the NOS content before reading aloud by prompting students with the reflective questions. This primed students to listen for NOS content during the read-aloud. A second technique involved planning locations in the text to stop and encourage discussion. These planned instances often aligned with the teacher asking either the discussion or reflection questions. Giving students time to discuss the NOS content as it aligns with the text encourages them to draw connections between the text and science practices in general. In contrast, teachers who read through a trade book without pausing at pre-planned "stations" provided little opportunity for students to think about and reflect on the concepts addressed.

Although any effective NOS instruction requires the teacher to have informed views of NOS, we want to acknowledge that specific sets of expertise are required to modify science trade books and/or develop educative curriculum materials. We stand ready to collaborate and partner with elementary teachers and district personnel toward this end.

25.4 Conclusion

This chapter aimed to provide an outline for how to effectively use trade books for NOS instruction in elementary classrooms. Although we have only provided examples of how this strategy can be used with elementary teachers in the context of Earth and space science, there is no reason to believe that this strategy cannot be used for life or physical sciences. Similarly, this strategy may be used to address any aspect of NOS, and not just those listed here. Many trade books provide opportunities to address multiple aspects of NOS, and over the course of an entire unit teachers may use different books to highlight various aspects. By going beyond the specific examples provided here, teachers may effectively use this strategy to incorporate NOS concepts in read-alouds throughout the science curriculum.

References

Abd-El-Khalick, F. (2002). Images of nature of science in middle grade science trade books. *New Advocate, 15*(2), 121–127.

Abd-El-Khalick, F., & Lederman, N. G. (2000). Improving science teachers' conceptions of nature of science: A critical review of the literature. *International Journal of Science Education, 22*, 665–701.

Abd-El-Khalick, F., Waters, M., & Le, A.–. P. (2008). Representations of nature of science in high school chemistry textbooks over the past four decades. *Journal of Research in Science Teaching, 45*, 835–855.

Aikenhead, G. (1988). An analysis of four ways of assessing student beliefs about STS topics. *Journal of Research in Science Teaching, 25*, 607–629.

Akerson, V. L., & Abd-El-Khalick, F. S. (2005). "How should I know what scientists do?—I am just a kid": Fourth-grade students' conceptions of nature of science. *Journal of Elementary Science Education, 17*, 1–11.

Akerson, V. L., & Hanuscin, D. L. (2007). Teaching nature of science through inquiry: Results of a 3-year professional development program. *Journal of Research in Science Teaching, 44*, 653–680.

Akerson, V., Nargund-Joshi, V., Weiland, I., Pongsanon, K., & Avsar, B. (2014). What third-grade students of differing ability levels learn about nature of science after a year of instruction. *International Journal of Science Education, 36*, 244–276.

Ball, D. L., & Cohen, D. K. (1996). Reform by the book: What is—or might be—the role of curriculum materials in teacher learning and instructional reform? *Educational Researcher, 25*, 6–14.

Banilower, E. R., Smith, P. S., Weiss, I. R., Malzahn, K. A., Campbell, K. M., & Weis, A. M. (2013). *Report of the 2012 national survey of science and mathematics education*. Chapel Hill: Horizon Research.

Brunner, J. L. (2016). *Enriching science trade books with explicit-reflective nature of science instruction: Impacting elementary teachers' practice and improving students' learning.* Unpublished doctoral dissertation. University of Illinois, Urbana-Champaign, IL.

Brunner, J. L., & Abd-El-Khalick, F. (2017). Representations of nature of science in U. S. elementary trade books. In C. V. McDonald & F. Abd-El-Khalick (Eds.), *Representations of nature of science in school science textbooks: A global perspective* (pp. 135–151). New York: Routledge.

Daisey, P. (1994). The value of trade books in secondary science and mathematics instruction: A rationale. *School Science and Mathematics, 94*, 130–137.

Davis, E. A., & Krajcik, J. S. (2005). Designing educative curriculum materials to promote teacher learning. *Educational Researcher, 34*, 3–14.

Ford, D. J. (2006). Representations of science within children's trade books. *Journal of Research in Science Teaching, 43*, 214–235.

Gibbons, G. (2007). *Galaxies, Galaxies!* New York: Holiday House.

Kelly, L. B. (2018). An analysis of award-winning science trade books for children: Who are the scientists, and what is science? *Journal of Research in Science Teaching, 55*, 1188–1210.

Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth-graders' views of nature of science. *Journal of Research in Science Teaching, 39*, 551–578.

Lead States, N. G. S. S. (2013). *The next generation science standards: For states, by states*. Washington, DC: National Academy Press.

Lederman, N. G. (1992). Students' and teachers' conceptions of the nature of science: A review of the research. *Journal of Research in Science Teaching, 29*, 331–359.

Lederman, J. S., & Lederman, N. G. (2004, April). *Early elementary students' and teacher's understandings of nature of science and scientific inquiry: Lessons learned from Project ICAN.* Paper presented at the Annual Meeting of the National Association for Research in Science Teaching, Vancouver, BC.

Lederman, N. G., & Lederman, J. S. (2014). Research on teaching and learning of nature of science. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of research in science education* (Vol. 2, pp. 600–620). New York: Routledge.

Lemke, J. L. (1990). *Talking science: Language, learning and values*. Westport: Ablex Publishing Corporation.

Mortensen, L. (2010). *Come see the Earth turn: The story of Léon Foucault*. Berkley: Tricycle Press.

National Governors Association Center for Best Practices & Council of Chief State School Officers. (2010). *Common core state standards for English language arts & literacy in history/social science, and technical subjects*. Washington, DC: National Governors Association Center for Best Practices, Council of Chief State School Officers.

Wahbeh, N., & Abd-El-Khalick, F. (2014). Revisiting the translation of nature of science understandings into instructional practice: Teachers' nature of science pedagogical content knowledge. *International Journal of Science Education, 36*, 425–466.

Walls, L. (2012). Third grade African American students' views of the nature of science. *Journal of Research in Science Teaching, 49*, 1–37.

Zarnowski, M., & Turkel, S. (2013). How nonfiction reveals the nature of science. *Children's Literature in Education, 44*, 295–310.

Chapter 26
Using a Participatory Problem Based Methodology to Teach About NOS

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26.1 Introduction

For many years, we have been teaching both undergraduate and graduate students about the nature of science (NOS), as a needed basis for a proper understanding of the scientific enterprise and knowledge. Either scientists or any other stakeholders somehow engaging with science need to understand more about NOS, as a construct derived but distinct from history, philosophy, and sociology of science (HPSS) as research field(s). As higher education teachers, we have been continuously engaged in helping students realize that understanding about NOS is not about adding a thin layer of erudition to their academic background, but is rather paramount for a proper understanding of the potentialities and conflicts in the relationship between the scientific endeavor and problem-solving in the real world. In these efforts, we have always inquired into methodologies that might lead to better outcomes in students' engagement and learning (e.g., El-Hani et al. 2004; El-Hani 2006, 2007). Since 2011, our inquiry led to the development of a problem-based learning (PBL) participatory methodology to teach about NOS, which we will describe in this chapter.

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W. F. McComas (ed.), *Nature of Science in Science Instruction*, Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_26

In the next section, we will address NOS as a pedagogical construct for teaching and learning about HPSS in diverse educational levels. Then, we will review some general aspects of PBL, giving emphasis to participatory approaches. We will then present a teaching strategy about NOS using a participatory PBL approach, which we will illustrate with teaching experiences at the undergraduate and graduate levels.

26.2 NOS as a Pedagogical Construct for Teaching and Learning About HPSS

In the last decades, we have witnessed a transition in the debates about NOS from advocating this pedagogical construct as part of the science curriculum in general terms to increasingly specific discussions about how to include it in science teaching. This scenario was accompanied by increasing debate on the very nature of NOS, which brought into dispute the most widely adopted conceptualization of this construct since the 1990s, based on a small number of general aspects, including aspects of the nature of scientific knowledge (NOSK) and aspects of scientific inquiry (SI) (e.g., McComas 1998; Lederman et al. 2002; Niaz 2009). This view on NOS has been criticized as insufficient and misleading, and some authors even advocated reframing the construct as the nature of sciences, given the disunified and plural nature of scientific work (e.g., Irzik and Nola 2011; Allchin 2011; Matthews 2012; Duschl and Grandy 2013; Hodson 2014; Erduran and Dagher 2014).

In this debate, we are close to a position expressed by Kampourakis (2016): the most widely accepted characterization of NOS (which he calls the “general aspects” conceptualization) can be a good starting point for teaching about NOS, and, from this approach, one can progress toward more complex aspects and contexts, considering how plural scientific work is. This position seems reasonable given that, on the one hand, we need to be attentive to the feasibility of teaching about NOS, especially at secondary education, which demands focusing on a small number of aspects, and, on the other hand, as in the case of any subject matter, teaching and learning about NOS should strive for progressing toward more complex constructs, increasingly aligned with our best current knowledge on the relevant issues.

To offer a proper ground for this argument, we need to consider that NOS is a pedagogical construct, proposed to be taught as part of the curriculum and related to academic knowledge in diverse fields gathered under the umbrella of HPSS. The complexity of establishing this pedagogical construct in a clear manner is reinforced by the fact that this umbrella field is composed of disparate approaches to science which are not always integrated – e.g., from history of science, philosophy of science, sociology of scientific knowledge, science and technology studies, and so on. Rather, these approaches may show troublesome relationships with one another, especially in the case of the relationship between sociological and philosophical studies of the scientific endeavor.

As any pedagogical construct, NOS needs didactic transposition (Chevallard 1989), that is, knowledge from the fields in HPSS should be transformed to originate a set of teachable ideas. This surely entails changes from the standpoint of what is philosophically, historically, sociologically discussed about science, and it is not proper to demand that the pedagogical construct should somehow mirror the relevant academic reference knowledge. If not transformed, knowledge from the HPSS fields will not be teachable. The general aspects approach can be seen, then, as a commitment to a particular way of understanding NOS as a pedagogical construct, which has developed along the abovementioned debates, as shown, for instance, by the differentiation between NOSK and SI.

But if we assume didactic transposition as a framework to understand the problem, how should we see the recent debates on NOS? From our perspective, the criticisms of the general aspects approach should be seen as exercises on what Chevallard calls "epistemological vigilance." What is under discussion is whether the didactic transposition of HPSS knowledge into the general aspects approach distorts so much what we know about science from historical, philosophical, and sociological standpoints that in the end the pedagogical construct is not in fact worth teaching and learning. With this in mind, we can be attentive to the pedagogical nature of NOS and exercise epistemological vigilance by evaluating how to teach about NOS. From this exercise, one can derive the idea of taking the general aspects approach as a starting point and then progressing toward more complex aspects, as one can do when teaching undergraduate and graduate students.

In the remainder of the chapter, we refer to NOS as a pedagogical construct we are aiming to address in our classrooms, and occasionally we will make reference to HPSS as the umbrella field of reference for legitimating in epistemological terms NOS as a pedagogical construct.

26.3 A Participatory PBL Methodology

Since 2011, we have been challenged to use Problem-Based Learning (PBL) in our teaching on NOS, due to our engagement in a Professional Master Program for environmental technicians and other stakeholders involved in decision-making, management, and other social actions in the environmental field (Pardini et al. 2013). In this program, PBL is an obligatory teaching approach. From our successful experiences with the Professional Master students, we were stimulated to also apply the approach in our teaching about NOS for undergraduate students, since 2015. Along both teaching experiences, we developed a participatory PBL approach using our teaching experience and knowledge alongside inputs from the educational literature. This participatory PBL approach includes more guidance than one often finds in PBL courses. To explain the nature and characteristics of our approach, it will be important then to examine PBL under the lens of educational methodologies, especially active and participatory methodologies.

Problem-based learning (PBL) was originally developed as a response to low levels of enrollment and general dissatisfaction in the field of medical education (Barrows 1996; Savery 2006), when McMaster University's medical school initiated its activities in the late 1960s. Since then, it has spread widely and has been applied in many diverse fields. In several meta-analyses, PBL has been shown to be effective with regard to long-term retention, skill development, and students' and teachers' attitudes and satisfaction (e.g., Albanese and Mitchell 1993; Dochy et al. 2003; Gijbels et al. 2005; Strobel and van Barneveld 2009; Shin and Kim 2013; Batdi 2014). Nevertheless, there are also dissenting appraisals in the literature (e.g., Colliver 2000; Neville 2009), and the conclusions regarding the efficacy of PBL can be disputed due to the methodological shortcomings of many studies (Albanese and Dast 2014).

PBL is student-centered and can indeed be located within a broader family of active methodologies. Teaching methodologies can be conceived as ways of organizing how we seek to promote teaching and learning goals. We will make use here of a broad but useful typology identifying three classes of such methodologies: passive, active, and participatory (Araujo 2017).

Passive methodologies are teacher-centered and lecture-based, often constraining the students to a passive position of listening to the teacher and trying to learn. Good teaching practice means, from this perspective, to offer the students a well-structured class, which reveals the logic of some subject matter, as a springboard for students' learning.

Active methodologies were a reaction to teacher-centered, lecture-based passive approaches. They originated with the British *New School*, in 1889, and from Britain were disseminated to Europe and other parts of the world (including Brazil) as innovative experimental approaches capable of overcoming the limitations of passive methodologies. PBL is one example of such innovative methodologies. As it is clear from their naming, *activity* is the key concept in these methodologies, being conceived as a way of generating experience, which leads to learning through the search of knowledge with functional value in the organism-environment relationship. These methodologies are centered on the students, who move from a passive to an active position, becoming builders of their own knowledge. It is activity and experience that are the springboards for learning, and good teaching practice means to create learning environments where students' activity can successfully lead them to knowledge with functional value.

Active methodologies show limitations resulting from the relegation of teaching to a secondary position while placing the students as the protagonists of the experiences taking place in the classroom and also from a biologically grounded approach to learning that tends to neglect the sociopolitical dimensions of both students' background and classroom practice. Moreover, something more than just appealing to activity and experience seems necessary when we have in view the development of a richer understanding of science-technology-society (STS) relations and a stronger socioenvironmental responsibility. The main reason for building a participatory PBL approach in our teaching practice concerns these limitations. This approach is also nourished by our engagement in critical STS education using socioscientific issues (SSI) (e.g., Conrado et al. 2016; Conrado and Nunes-Neto 2018; Conrado et al. In press).

Participatory methodologies are grounded, as stated in their naming, on participation, sharing, and cooperation, and their advocates are critical of active methodologies for what they consider to be a biologizing tendency of the new school, which entails an autonomy of the learning subject in relation to his or her sociohistorical circumstances. Sociopolitical issues become, thus, a central concern in participatory methodologies, which avoid treating either students or teachers as protagonists. Rather, it is the knowledge available at a given sociohistorical circumstance that becomes the center of the teaching and learning process. Accordingly, it is ascribed to the teacher the key role of mediating the relation between learners and knowledge. Teachers are required to offer guidance and scaffolding for the students to the extent required by their relation to what is to be learnt. It is above all the higher level of guidance and scaffolding that differentiates the role of the teacher in active methodologies from the kind of mediation she should offer in a participatory approach.

Even though lack of enough guidance is a criticism voiced against PBL and other active methodologies (e.g., Kirschner et al. 2006; Sweller et al. 2007; Alfieri et al. 2011), it is not the case that all PBL approaches suffer from this problem. As Hmelo-Silver et al. (2007) argue, in response to Kirschner and colleagues, PBL is often highly scaffolded. Similarly, Hmelo-Silver (2012) identifies, in a review of many international PBL programs, a number of approaches that diverge from the traditional PBL model, offering more guidance to the students regarding relevant concepts, readings, examples, planning worksheets, among other ways of providing scaffolding to the problem-solving activities.

A central element in PBL is the use of ill-structured problems, that is, problems that allow multiple ways of solving them, using a diversity of strategies, depending on the students' decision on how to tackle them. PBL also demands properly prepared problems, which are authentic in relation to professional or real-world practices relevant to the students. The fact that a problem is ill-structured does not mean that teachers shouldn't mediate between students' actions and the knowledge they should learn. This mediation is particularly clear in PBL approaches in which students are encouraged to analyze the proposed problems in order to establish the key issues involved; determine their knowledge gaps, i.e., what they need to learn to solve the problem; and pursue the missing knowledge autonomously.

Their autonomy is not complete, however, because instructors should act as mediators between the students and the relevant knowledge. This mediation does not entail guiding them directly toward the sources of such knowledge but asking them the kinds of metacognitive questions the teachers want the students to ask themselves (Barrows 2002; Savery 2006).[1] The idea is to empower learners with the

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[1] By "metacognitive questions," we mean questions about their own thinking processes and practices. That is, rather than providing them with ready answers or readings, we will incite them to think through how they are looking for and reading the sources and how they are dealing with knowledge by themselves, among other aspects.

skills and confidence to seek the knowledge and information they need, to integrate theory and practice, and to apply knowledge and skills to develop viable solutions to authentic problems.

26.4 Applying Participatory PBL Methodology to Teach About NOS

We have been using PBL, in a participatory approach, to teach about NOS in two contexts: in an undergraduate course on the history and philosophy of science (entitled "Evolution of Scientific Thought") offered to biology, oceanography, and interdisciplinary bachelor (akin to college in the US university system) students and in a course named "introduction to scientific knowledge," offered as part of a Professional Master Program in Ecology Applied to Environmental Management.

Many reasons excited us about using the participatory PBL approach. First, we were quite interested in the possible PBL outcomes concerning students' skills and long-term knowledge retention. Second, we thought that it might provide a more challenging, motivating, and enjoyable approach than the previous reading-, seminar-, and lecture-based approaches we were using. Third, it seemed an appropriate approach to teach about NOS to students enrolled in natural sciences programs, who are not familiar with these topics. In the case of the Professional Master Program, it is important to highlight that all the courses use a PBL approach, as a curricular decision following from the judgment that this approach is more adequate to foster the kinds of ability we intend our student to develop, considering that they are professional environmental decision-makers and/or managers who work solving problems all the time.

The planning of our courses follows general guidelines for preparing participatory PBL approaches developed by the chapter authors, which were elaborated as guidelines for the teachers from the Professional Master program and are periodically presented to them in an in-service teacher education initiative. We also use these guidelines in planning the undergraduate course on the history and philosophy of science.

Table 26.1 offers an overview of the planning of the participatory PBL approach to the graduate course "Introduction of Scientific Knowledge." In the following sections, we will describe in more detail the planning steps and teaching proposals, with illustrations from both the undergraduate and graduate courses.

26.4.1 General Argument and Key Questions in Teaching Planning

Curriculum Goals (1), Course Goals (2), and Student Profiling (3) The general guidelines for planning a participatory PBL approach depart from basic questions for curriculum building and implementation: what is the contribution of the courses

Table 26.1 Planning a participatory PBL approach for the course "introduction to scientific knowledge," from the Professional Master Program in Ecology Applied to Environmental Management

	Action	Example
1	*Curriculum goals* To list the general program curriculum goals to which the course should contribute	To educate environmental professionals who are able to access and critically assess scientific knowledge and incorporate it into socioenvironmental problem-solving
2	*Course goals* To list the specific educational goals of the course itself, building a clear conception of how they are articulated with the general program curriculum goals	To create opportunities for the students to develop NOS conceptions that allow them to understand how science internally works and the relations between science, technology, society, and environment, based on appropriate didactic transposition from HPSS knowledge To create opportunities for the students to develop abilities to access and assess scientific knowledge that is relevant to socioenvironmental problem-solving
3	*Student profiling* To characterize the profile of the students enrolled in the course	Practitioners engaged in environmental decision-making and management, or related activities, including technicians from environmental state and federal agencies and environmental consulting firms, as well as teachers, with diverse backgrounds (engineers, biologists, sociologists, lawyers, and so forth)
4	*Central message* Based on (1), (2) and (3), to elaborate the central message that the course intends to convey to the students	Efficacy in environmental decision-making is contingent upon the understanding of how socioecological systems work. Different scientific fields produce and rigorously appraise knowledge that contributes to successful and reliable modeling about the functioning of socioecological systems. These fields can work interdisciplinarily, building integrated scientific knowledge bases for tackling socioenvironmental problems, and transdisciplinarily, also integrating other forms of knowledge (say, practitioner or traditional knowledge) (Tress et al. 2005). When such integrated knowledge bases are available, they can be used to build socially robust orientations for socioenvironmental decision-making (Scholz 2017)
5	*Key questions* To formulate key questions that, once answered, can lead to the general argument of the course (4)	1. What characterizes science as a form of knowledge? 2. What are the relations between evidence, arguments, and conclusions? 3. How can we infer reliable conclusions from evidence? 4. How can we evaluate the reliability of claims that support socioenvironmental decision-making? 5. How can we evaluate the reliability of scientific sources? 6. How can we retrieve reliable scientific information for socioenvironmental decision-making? 7. What should be the role of science in socioenvironmental decision-making? 8. How are scientific and social values related? 9. How can we advance in building interdisciplinary and transdisciplinary knowledge bases for socioenvironmental decision-making? 10. What is (or should be) the role of scientific knowledge in policy-making and decision-making?

(continued)

Table 26.1 (continued)

	Action	Example
6	*Socioscientific issues as cases for analysis* To elaborate a case (hypothetical or real) based on a socioscientific issue that allows exploration by the students in order to answer the key questions (5)	One of the cases offers a historical narrative of social controversies triggered by a project to channel an important river in the city where we live, highlighting arguments for and against the channeling
7	*Problems* To formulate a sequence of problems related to the case (6) that, once solved, allow the students to elaborate answers to the key questions (5)	1. Which pieces of evidence are used in the arguments used for supporting antagonistic positions in the controversy? Are they reliable? 2. Do these arguments find support in the scientific literature dealing with urban rivers channeling? 3. Should this scientific knowledge influence decision-making about this socioenvironmental problem? How?
8	*Learning outcomes* To detail the (conceptual, practical, and attitudinal) learning outcomes expected to result from the resolution of each problem	See Table 26.2
9	*Scaffolding and systematizing activities* To plan lectures to systematize relevant knowledge and consulting sessions for scaffolding problem-solving (7), but without offering ready-made solutions	*Lectures* 1. Kinds of knowledge 2. Argumentation 3. Strategies for bibliographic survey and source evaluation 4. Perspectives on the relations between science and environmental management
		Consulting sessions 1. Meeting with the residents' association from one of the districts affected by river flooding 2. Meeting with an environmental movement for the defense of the river
10	*Learning and participation evaluation* To evaluate problem-solving reports focusing on conceptual, practical, and attitudinal dimensions To evaluate participation focused on practical and attitudinal dimensions, including self-evaluation, peer evaluation, and tutor evaluation To gather students' impressions about the fulfilling of the expected learning outcomes for each problem-solving activity (8)	To develop and apply evaluation protocols for problem-solving reports and participation To ask each student whether the pedagogical goals and learning outcomes proposed for each step of the course were reached, and how efficacious was each problem for fulfilling them (within the constraints imposed by the time available to its resolution)

Source: Elaborated by the authors

Table 26.2 Example of socioscientific issue, problems, and guiding questions used in participatory PBL learning at an undergraduate course on history and philosophy of science

Socioscientific issue: As members of the Brazilian National Congress, the students should vote for or against a law project to replace a label to indicate transgenic items in food products by a simple statement, only when these items are above 1%. The modification is justified by claiming that the label is detrimental to food product marketing and there is no scientific evidence for harmful effects of transgenics on health or environment.

Parts	Problems	Guiding questions
1	After reading the two reports (a National Academy of Sciences report and a Greenpeace webpage), you should decide to vote for or against the law project proposing to eliminate the label that indicates that food products contain transgenics. You should write a 1–2 page document: (1) Stating and justifying your vote (2) Discussing what scientific evidence show regarding the impact of transgenics on health and environment (3) Explaining which role evidence played in the decision-making, whether and how they were used to base your voting	1. What is scientific evidence? 2. What role should evidence play in decision-making in society? 3. What does the scientific literature report on the impacts of transgenics on human health? 4. What does the scientific literature report on the impacts of transgenics on the environment? 5. What do the evidence suggest regarding your decision to vote for or against the label indicating the presence of transgenics in food products? 6. What was your decision concerning the voting? 7. How do you justify this decision?
2	To what extent can you be sure about the impacts of transgenics on health and environment based on scientific evidence? You should write a 1–2 page document answering this question	1. What role do scientific evidence play in the acceptance or rejection of a hypothesis? 2. When a hypothesis is confirmed or refuted by available evidence, can we be sure about its truth or falsity? 3. Do available evidence on transgenics make it possible to justify once and for all your decision on how to vote? 4. Or would there still be room for doubt? But if we had doubts, would that make it useless to appeal to evidence? What role could evidence play in the acceptance or rejection of a hypothesis when there are doubts even in the presence of available evidence? 5. What role could evidence play in decision-making in society when there are doubts despite available evidence?

(continued)

Table 26.2 (continued)

Socioscientific issue: As members of the Brazilian National Congress, the students should vote for or against a law project to replace a label to indicate transgenic items in food products by a simple statement, only when these items are above 1%. The modification is justified by claiming that the label is detrimental to food product marketing and there is no scientific evidence for harmful effects of transgenics on health or environment.		
3	You received letters from several of your voters questioning the reasons why you decided to vote as you did. One of the questions concerns which reports, papers, or other works were used to ground the decision on how to vote. You need to explain and justify to your voters how the bibliographic surveys were performed and which criteria have been used to decide which works to read in order to constitute the knowledge base used to ground the decision You should write a 1–2 page document explaining and justifying the bibliographic survey and selection criteria	1. Have you performed a systematic survey of works to support your decision? If not, it is the time to do it. If yes, how have you performed this search? 2. Do you consider the searching procedure and the criteria for selecting works to read appropriate and sufficient? 3. If you consider they were not appropriate and sufficient, you will need to rethink the searching procedure and the selection criteria and perform more bibliographic surveys in order to select again a set of works to read 4. Once you read the new selected literature, which conclusions do you reach about the impact of transgenics on human health? 5. Once you read the new selected literature, which conclusions do you reach about the impact of transgenics on the environment? 6. Once you drew conclusions on the impact of transgenics using the new literature, do you wish to make any change in the decision taken about your vote concerning the presence of the transgenic label in food products? 7. How do you justify the changes (if any) in the decision?

(continued)

Table 26.2 (continued)

Socioscientific issue: As members of the Brazilian National Congress, the students should vote for or against a law project to replace a label to indicate transgenic items in food products by a simple statement, only when these items are above 1%. The modification is justified by claiming that the label is detrimental to food product marketing and there is no scientific evidence for harmful effects of transgenics on health or environment.		
4	In a letter, one of your voters point to a work that in her opinion seems decisive for guiding your vote against the proposal to eliminate the label indicating the presence of transgenics in food products (Séralini et al. 2014a, "Republished") She calls attention to the fact that the study was publicized by the media and one cannot appeal to ignorance if it was not taken into account in decision-making about the label. [links to Brazilian media articles and TV shows] Your voter asks: are there value judgments involved when scientists choose what and how to investigate, and people and organizations in society decide to use or not and how to use scientific evidence and knowledge? You should write a 1–2 page document answering this question	1. Did you take this study into account when deciding your vote? What are your views about the paper and the newspaper articles and videos? 2. If you took the study into account, please explain to your supporter how did it influence your vote? 3. If you did not take it into account, analyze the vote you gave critically under the light of this study (no matter if you voted for or against the presence of the transgenic label) 4. Considering the *National Academy of Sciences* report, the *Greenpeace* webpage, and the paper by Séralini et al., do you identify issues associated with values in the choice of research goals, the decisions on inquiry methods, and the conclusions obtained? Which issues? 5. Considering the use of these documents in society, do you identify value issues involved? Which ones? 6. It is common to say that science is objective. But what is objectivity? Do the value issues you identified affect or not the objectivity of science? If in your view they do not affect, explain why. If in your view they do affect, explain why and think of possible ways scientific work could still be reliable despite value issues

Source: Elaborated by the authors

to educate the kind of professional intended by the higher education (undergraduate and graduate) programs? What is the role of the courses in the overall logic of the higher education programs, and how should they contribute to implement that logic? What is the background of the students attending the courses, and how should the activities be structured to effectively engage them? Attention to these aspects will help the planning of the PBL activities in different curriculum components to adhere to the pedagogical project of the course and also their adaptation to the specificity of the different groups of students.

Central Message (4) In order to have a clear view of the nature of the problems used in each course, and of all other items in the planning, and also to guide tutors' interventions along the activities, we build a clear statement of what is the central message we intend to convey. The central message in the course "introduction to scientific knowledge" is provided as an example in Table 26.1.

Key Questions (5) The construction of the problems continues by deriving key questions to be answered from the central arguments, which offer a clear perspective on the knowledge, skills, and attitudes the problems should bring to the scene. For the abovementioned course, we illustrate the key questions in Table 26.1.

When the key questions are formulated, we can clearly establish which NOS aspects will be tackled. Considering the key questions illustrated in the table, we can see, for instance, how discussions on the characteristics of science as a form of knowledge lead to an examination of how to differentiate science from other human endeavors. This also leads to a reflection on the prospects and limits of scientific understanding. The role of evidence in the justification of scientific knowledge or in decision-making relying on scientific outputs will be targeted if one discusses how evidence, arguments, and conclusions are related. When one deals with tentativeness in science, to ponder about why scientific knowledge can be reliable and how to ascertain reliability will be just natural. To deal with the issue of reliability can lead one to consider the durability of scientific knowledge, despite its tentativeness, as well as the idea that a self-correcting enterprise like science should make use of reliable practices, from which reliable knowledge can follow.

In both our undergraduate and professional master courses, we cover subjects related to the three key aspects of NOS described by McComas (2019, this volume): tools and products of science, scientific knowledge and limits of science, and human elements of science. We do not address these aspects separately, but in an integrated manner, when we deal, for instance, with the role of evidence in science, the diverse methods (like observation, systematic comparisons, experiments) and diverse modes of reasoning used (induction, deduction, explanatory inference, or abduction) shared by different sciences. In the courses for undergraduate students, more advanced aspects related to this topic include, for instance, Bayesian theories of confirmation and the relationship between evidence, testing, and the social organization of scientific work, with a balance between competition and cooperation, as well as between criticism and trust among scientists from a given generation and also scientists across generations (e.g., Godfrey-Smith 2003). For the graduate students, as they are professionals active in environmental decision-making, the most advanced features concern how evidence and the appraisal of reliability are related to decisions they may be taking in a daily basis.

We also consider the tentative, durable, and self-correcting nature of science, trying to progress in the discussion of error-based learning and the growth of empirical knowledge (e.g., Mayo 1996), with connections to decision-making by our professional students.

We give much attention to the role of (inter)subjectivity and bias in scientific work and the interactions between society, culture, and science, advancing in the discussion of science as a value-laden enterprise (as any human enterprise), addressing specific proposals on how the interplay among scientific work, values, and policies takes place (e.g., Lacey 1999; Kitcher 2001), and considering how objectivity as an epistemic value has a history of its own and enters into relation with trained judgment in the intersubjective processes of knowledge appraisal in science (Daston and Galison 2007). Again, in the case of the professional students, these aspects are connected with their practices in decision-making.

26.4.2 Socioscientific Issues as Cases for Analysis

Cases for Analysis (6) After establishing the central message and key questions, the next step is to elaborate a document describing situations that are either inspired by or represent real cases close to the students' experience (for instance, environmental management or decision-making for the Professional Master students) or are at least as authentic as possible (e.g., decision-making situations that are familiar to the undergraduate students, say, well-publicized in the media). These situations should provide appropriate grounds for developing problems leading the students to tackle the key questions in each course.

We use socioscientific issues (SSI) for building the problems to be used in the classroom. SSI are complex controversial problems or situations faced by current societies in which scientific knowledge is fundamental to the origins, understanding, and/or search for solutions and which can be transposed to the classroom as a teaching and learning tool in science education, particularly to address STS relationships and ethical aspects of societal problems and scientific inquiry (e.g., Sadler 2004; Zeidler et al. 2005; Levinson 2006; Conrado and Nunes-Neto 2018).

Introductory texts or scenarios are elaborated to frame the problems. They establish a background for decision-making. In order to increase the fidelity of the texts and problems with regard to the students' experiences, we sometimes submit them previously to the critical appraisal of people engaged in corresponding problems, say, environmental technicians, in order to guarantee that they are as authentic as possible. An example of such a case is given in Table 26.1.

Problems (7) We then formulate the problems intended to address the key questions (as exemplified in Table 26.1). These problems pose progressively more difficult challenges to the students. Role-playing is involved in the problem-solving activities. The problems address different dimensions of contents, namely, conceptual (what we should know), practical (what we should know how to do), and attitudinal (what should we be) (Coll et al. 1992). To address these dimensions, we use the critical and multidimensional approach to contents proposed by Conrado (2017) and Conrado and Nunes-Neto (2018).

Learning Outcomes (8) When elaborating each problem, we make explicit the conceptual, practical, and attitudinal dimensions we intend to cover and the learning outcomes expected. This is useful to keep in mind that the goal of the problem-solving work is not only to foster understanding of philosophical or scientific knowledge but also of practices and attitudes in relation to the knowledge needed to deal with different situations and problems. It is also useful to plan the conceptual contents that will be systematized in the lectures and the scope of consulting sessions, as well as to guide the interventions of the tutors during the student teams' efforts to solve the problems.

In the construction of the problems, we explore the idea that different learning outcomes should be envisioned when planning teaching, involving increasingly more challenging cognitive skills. For this purpose, we employ the revised Bloom's taxonomy proposed by Krathwohl (2002) to identify learning goals to be achieved in each problem. In particular, we use the proposals made by one of the authors of this chapter and colleagues on how to use this taxonomy along with PBL in ecology teaching (Lewinsohn et al. 2015). By using this taxonomy, we consider the skills of remembering, understanding, applying, analyzing, evaluating, and creating. In relation to the specific purposes of our teaching approach, we intend that the students develop skills such as *remembering* key scientific and philosophical concepts, *understanding* how scientific and philosophical concepts relate to their (professional) activities, *applying* scientific and philosophical knowledge in their daily activities, *analyzing* scientific and philosophical knowledge associated with practical problems, *evaluating* practices incorporating scientific and philosophical knowledge, and *creating* solutions to practical issues based on scientific and philosophical knowledge. Learning outcomes are exemplified in Table 26.2.

The practical aspects can, at least in part, be developed by using the Maastricht seven-step approach (Gijselaers 1995; Maurer and Neuhold 2012). The intention of this strategy is to facilitate and structure students' learning processes within PBL, by prompting them to organize their work around the following steps: *clarification* of terms and concepts involved in the problem; clear *formulation of the problem statement*, reaching the highest possible agreement among the students in the team; *brainstorming*, in which previous ideas the students have and deem relevant to solve the problem are brought to team discussion, in order to attempt to reach a solution based solely on prior knowledge; *organization of brainstorming outcomes* in an attempt to solve the problem; if they do not solve the problem with prior knowledge (which is usually the case), *formulation of learning goals*, that is, knowledge gaps hampering problem-solving; *self-study*, in which each student or group of students autonomously looks for sources to fill the knowledge gaps; *post-discussion*, in which what was learnt in the self-study is brought to the team and, once again, they try to solve the problem and, if they do not succeed, another round of self-study takes place, focusing on knowledge gaps identified from the limits of the current solution (surely, time limitations common in educational settings intervene here, constraining the number of rounds of self-study); and *metacognitive reflection* on the problem-solving and learning processes, considering issues like team management, study strategies, among others, with the goal of improving individual and teamwork in future problem-solving experiences. Students are regularly encouraged by both professors and tutors (when available) to use the seven-step approach during problem-solving.

As part of the practical dimension, we also encourage the students to use Toulmin's argumentative model (Toulmin 2003) to build their arguments. This model is explained in the beginning of the courses. To include this aspect is important to provide opportunities for students' learning about how to build valid and solid arguments, which they scantily find along their educational experiences.

Regarding the attitudinal dimension, the efforts to solve the problems proposed for classroom work tend to involve discussions about (and laden with) values. Therefore, it is crucial that the teacher reflect upon the value issues involved in the proposed situations and problems, in order to take the most advantage of the opportunities to engage students with attitudinal aspects. We also strive for interconnecting the increasingly challenging problems with one another, in order to give the students a greater chance of building a systematic and integrated view about NOS.

Scaffolding and Systematizing Activities (9) When students are engaged in problem-solving, they establish meaningful relations between their previous conceptions, the knowledge of the diverse fields relevant to tackle the problem, and the situated character of the issues at stake. This is no doubt quite fruitful for their learning on the knowledge fields and their relations to decision-making, management, teaching, or other actions. However, this also means that they engage with knowledge from several fields in a piecemeal manner, according to the logic of the problem, not of the field itself. Surely, this is an advantage since it shows how we need to intertwine knowledge from different sources when solving real-world problems. But it may also bring difficulties to understand in a coherent, deep enough, and consistent manner the knowledge from academic fields. Moreover, it is not really possible in typical classroom times to deal with decades, even centuries of knowledge built on distinct subjects by the academic communities. On the one hand, this raises issues related to proper didactic transposition (Chevallard 1989). But on the other it also means that we need more than just active engagement of the students with the problems for them to master relevant knowledge. This is the major reason why we use some lectures properly located within the series of activities – for instance, after they delivered problem-solving reports – in order to systematize relevant knowledge, striving for apt didactic transposition. Moreover, specific situated information may be needed to solve the problem, which can be accessed through consulting sessions with stakeholders engaged with the kinds of problem proposed for classroom work. Both lectures and consulting sessions are exemplified in Table 26.1.

Learning and Participation Evaluation (10) After the students delivered the problem-solving report, the learning goals used in the planning are shown to them, and they are asked to evaluate whether the problem allowed to fulfill the planned goals. This provides valuable information for the improvement of the cases and problems.

We use an evaluation strategy that gives the students partial control of their own assessment and of the assessment of their peers. One of the key characteristics of PBL approaches is that they demand that students take substantial control over their behavior in the classroom and the outcomes of their performance. This is an important feature because, as discussed by most social cognitive theories of motivation, the individuals' belief about how much control they have over their behavior or the outcome of their performance is a key aspect of an intrinsically motivated learner (Pintrich et al. 1993). For instance, Pintrich (1989) found a positive correlation between internal control beliefs and college students' use of deep processing and metacognitive strategies as well as their actual performance on class exams, lab reports, papers, and final grades. Conversely, authority structures that do not allow students much choice or control over their activities decrease the probability that they are oriented toward mastering the content at stake, rather than just external rewards (Ryan et al. 1985; Ames 1992).

These findings indicate how important it is to lend students control over the learning processes and, also, about the assessment of the outcomes of their performance. Surely, PBL offers students a high degree of control over their cognitive and metacognitive strategies, but in our courses, we go one step further. We treat assessment as a key control locus for the students' activities. To assess student participation, we use self-evaluation, peer evaluation of the team members, and tutors' assessment. Thus, students are given power over their own assessment, in order to increase their internal control beliefs, and also over the assessment of their peers, offering them tools to appraise the extent to which their colleagues are sharing responsibility for the tasks. In tutors' assessment, we consider practical aspects, such as the distribution of activities per student, each students' contribution to team discussion and report writing, and their efforts to search and explain to their colleagues works relevant to the cases in study, among other features. We also consider attitudinal aspects related to plagiarism, students' respect to each other's positions and opinions, and an orientation toward mastery rather than merely reward during problem-solving.

In the assessment of the problem-solving reports, we consider conceptual, practical, and attitudinal dimensions. In the conceptual dimension, we assess whether conceptual contents were correctly presented by the students in their reports. In the practical dimension, we analyze argumentation quality, writing, and adequate use of citations. In the attitudinal dimension, we evaluate whether the students appealed to plagiarism, and the cohesion and organization of the arguments, in order to check whether they carefully revised and copyedited the reports.

26.4.3 Exemplifying the PBL Participatory Approach for Teaching About NOS in an Undergraduate Setting

In the undergraduate course, the general argument is that the construction and justification of scientific knowledge involve a complex interplay between empirical evidence and model- and theory-building, which should be understood in terms of the social organization of scientific work at a given time (e.g., involving a balance between competition and cooperation, and between criticism and trust) and across times (e.g., coordinating the work of different generations of scientists) (e.g., Godfrey-Smith 2003), and considering that science is not value-free, but involves also a complex interplay among scientific work, values, and policies (e.g., Lacey 1999; Barker and Kitcher 2013). From this general argument, key questions are derived: to give just an example, how does the interplay between criticism and trust operate in a scientific community to generate methodological decisions of leaving some pieces of knowledge immune to falsification (as in Lakatos' hard cores of research programs or Kuhn's paradigms), while other pieces are subjected to constant and rigorous testing?

We have a set of socioscientific issues (SSI) ready for use in the classroom. They are organized as cases with several parts, each part corresponding to a problem to be tackled, with distinct distributions of conceptual, practical, and attitudinal dimensions.

One example concerns a Brazilian law issued in 2005 that establishes that food products containing transgenics should be labeled with a symbol () to guide consumers in their decision to use such products (see Table 26.2). A modification of this law was proposed in 2015 stating that the label is to be replaced by a simple statement that the product contains transgenic items, which should only be included when these items amount to more than 1% of the product composition. This law project was approved by the lower house of the Brazilian National Congress (the Chamber of Deputies) in 2016 and is now under appreciation by the upper house (the Federal Senate). This SSI was developed from previous studies by our group (Carvalho et al. 2018) and is familiar to the undergraduate students, as the subject has been widely aired in the Brazilian mass media.

The students should work as a team and play the role of members of the National Congress who have to decide how to vote on the bill proposing the modification of the transgenic labeling. They are presented with two justifications for the modification: the symbol is detrimental to the marketing of food products, and there is no scientific evidence for the claim that transgenics are harmful to either health or environment. They are given two documents retrieved from a survey made by their assistants for informing them about the position of the scientific community about the risks associated with transgenics: a *Greenpeace* website on environmental and health impacts of genetically modified crops (Greenpeace 2011), clearly inclined against transgenics, and a report by the *National Academy of Sciences of the United States* (NAS 2016), which show a more favorable leaning toward transgenics but is also more robust than the *Greenpeace* website. This bibliographical survey is deliberately biased and thus not helpful for an informed decision-making, because we want them to be able to make this judgment by themselves and plan and perform their own surveys.

In the first part of the SSI, they are asked to decide whether they will vote for or against the law project, justifying this decision, discussing what scientific evidence show about the impacts of transgenics on health and environment, and explaining what role was played by evidence in the decision-making process. At this point, there is no guidance for performing new surveys to obtain further scientific literature on the subject. The intention is that they reach the conclusion that better surveys are needed by themselves. Also, the content of the law project is presented as often aired in the media, focusing on the elimination of the label and giving less attention to other aspects, such as the presence of a statement that the food product contains transgenics.

The guiding questions provided to the student teams lay at this point greater emphasis on conceptual aspects, as we can see in Table 26.2. These questions guide them in progressing from discussing conceptual issues to assessing the scientific literature to making and justifying the decision.

We still need to do a systematic empirical study on our teaching experience with the PBL participatory approach, but some highlights on how it is working in the classroom can be obtained from teacher's diaries. From previous experiences using this case, we derive some expectations on how the students will handle the problems, which have been fulfilled along the semesters. We expect that they already have some ideas about what is evidence since most of them are engaged in natural sciences undergraduate courses and several students are also doing scientific training in labs. For the same reasons, we also expect that at least initially they take positions for evidence-based decision-making without putting into question what does it mean to propose that decision should be grounded mainly or even exclusively on evidence when there are relevant issues related to other stakeholders' views, values, and interests in a democratic society. We also expect that they notice the necessity of doing a better bibliographic survey to reach conclusions about what the scientific literature says about the impacts of transgenics. After surveying the literature, however, they are likely to be unable to reach a conclusion that seems convincing enough, given the perception that we do not have enough studies for that and the fact that several students will raise questions about who is funding the studies, which values and interests are involved, and so forth. It is likely then that they will find a need to appeal to other reasons than scientific evidence to ground their voting decision, even though they will not disregard scientific evidence at all.

As a more specific point, we can mention that at least some students state a fruitful view of evidence as something that increases or decreases the probability of a claim (cf. Blackburn 2008). This view opens the door for the discussions along the case and especially in the systematizing lectures on how to ground intuitions on the relationship between evidence and probability, from the logical positivists' failure to build an inductive logical theory of science to the current efforts for building a Bayesian theory of confirmation (e.g., Godfrey-Smith 2003; Barker and Kitcher 2013).

Along the semesters, all of the student teams decided to maintain the transgenic label, but they generally do not feel that scientific evidence offer a reliable basis for decision-making on the issue. Then, they rely on other reasons for decision-making, for instance, appealing to the precautionary principle and to laws protecting consumers' rights, based on the argument that a buyer has the right to know what is contained in what she buys. But they usually lose from sight that this right is supposedly preserved in the new law that replaces the label by a simple statement and thus do not discuss how damaging could be the substitution of the symbol indicating the presence of transgenics by a mere statement on the food label.

A rewarding outcome from the first time we used this SSI was when one student team built an elaborate argument that the label had to be maintained in the food products but needed a modification. They argued that the label currently used has the same design of symbols clearly indicating danger (say, due to radioactivity). But what they could draw from the scientific literature was that risks were not clearly established but still may exist. Thus, a symbol indicating precaution in using the products seemed more appropriate to them:

> … playing the role of Federal Deputies in this case, we vote against the law project that proposes the elimination of the symbol indicating the presence of transgenics in food products, since it is, according to the Brazilian Consumer Protection Code, a consumer's right to have access to adequate information and freedom of choice, no matter if the use of transgenics is harmful or not to human health. Furthermore, research on the possible impacts that the technique can cause to the environment and to human health is limited. Long-term nutritional and toxicological studies are needed. Yet the symbol used for transgenic food can be questioned, since it not only informs about the content but also carries an inexorably negative value, pointing to a harmful potential. We consider that there is still a large difficulty that society understands the message conveyed by the symbol, which has not only the goal of informing whether a given product contains transgenics or not, but also of granting the consumer the right of opting for consuming transgenic-free products as a political and precautionary act…[2]

In the second part, they are faced by a voter's challenge regarding to what extent they can be sure about the impacts of transgenics on health and environment based on scientific evidence. The intention is that they engage in epistemological discussion on the relation between evidence and scientific claims. The guiding questions are shown in Table 26.2.

Conceptual issues are still the major focus in this part, even though it is clear that practical and attitudinal aspects are also involved. We expect that when pondering on the first guiding question they will tend to assume the view that evidence is a

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[2] The excerpts from students' works were freely translated by the authors.

neutral arbiter for the acceptance or rejection of scientific claims, which is not warranted by current discussions in the philosophy of science, but is likely to be present in their science learning and scientific training. The second question suggests, then, that they need to put into question this way of thinking about evidence. That's because to be sure about truth or falsity is too strong a position when they start thinking about the nature of empirical testing. But if the second question does not prompt doubt about their views on the role of evidence in justifying empirical claims, the third question is likely to do it. We expect, then, that the fourth question opens room for developing a more sophisticated view on the relation between evidence and empirical claims, in which they can elaborate on the idea that, even though we cannot be absolutely certain about the truth or falsity of a claim, we are still able to make judgments regarding its reliability when we respect the available evidence. This becomes a more complex topic for them in the last guiding question, which projects the situation from supporting a scientific claim to make decisions on societal issues. We expect that, in this case, they will be quite hesitant on the role of scientific conclusions because, after they surveyed the literature, it will be hard for them to reach a position where they can say something reliable from the available evidence. This is alright because that's what we indeed get from a survey on the scientific literature about the risks of transgenics for health and environment: more studies are needed, and we need to worry a lot on biases resulting from funding, values, and interests (*cf.* NAS 2016).

From our teacher's diaries, we can see that the expectations above have been generally fulfilled in the classroom. The second part of the SSI encourages the students to develop more sophisticated views on the role of evidence in decision-making about scientific claims and societal issues. This prompts them to be attentive to the systematizing lectures, where we address the relations among reason, evidence, and methods and present respect for evidence when evaluating claims about the natural world as a sign of rationality (see Kelly 2016). We also take this idea as a springboard to openly criticize the views of a post-factual or post-truth world, that is, the trend in current societies (and even governments) to ignore factual evidence (particularly, scientific) in political decision-making regarding subjects in which such evidence are clearly of key importance, for instance, about global warming policies (Fellet 2018).

The third part requires that the students, again when questioned by their voters, inform which papers, reports, and other works they used to ground their decision about the project law. More specifically, they are asked to explain and justify the bibliographical surveys they did and the criteria used to select the works to constitute the knowledge base used to support the decision. If they didn't make surveys, they would need to perform them at this step, but this never happened in any occasion we used this SSI. The guiding questions are presented in Table 26.2.

Practical aspects play a central role in this step, albeit conceptual and attitudinal dimensions are present, particularly when the students engage with new literature. From our classroom notes, we can see that typically the student teams are not satisfied with their surveys and engage in discussion on what bibliographic databases, keywords, and logical combinations of keywords they should use. They also tend to agree on the need to refine their criteria to choose works to examine in order to support the decision. Therefore, they typically do new searches at this step and refine the selection of works to read. Naturally, they ponder again about their prior decision, but they usually stick to the decision of maintaining the transgenic label, because they based their decisions on other reasons than the scientific literature. On reading new sources, it is hardly the case that they find some scientific groundbreaking work that makes them change their positions.

In the fourth part, a voter questions them about a work she regards to be decisive for the decision on the transgenic label, namely, Séralini et al. (2014a, "Republished"). This is a work that made the headlines all around the world as it reported long-term toxicity of Roundup© herbicide and a Roundup©-tolerant genetically modified maize. Indeed, the voter calls attention to the fact that this study was widely publicized by the mass media, such that if the students ignored it, they cannot appeal to the excuse that it was some obscure study. This study led several countries to decide for adopting more restrictive laws concerning transgenics since it showed tumorigenesis induction in mice, but after hot debate and relevant socioeconomic consequences, the paper ended up being retracted. Deliberately, we indicate to the students a republished version of the paper, not the original one (Séralini et al. 2012, "Retracted"). They should discover by themselves that they are dealing with a retracted article.

Here we will not discuss the specific aspects of the Séralini case, which can be checked by the reader in the literature (*e.g.*, Portier et al. 2014; Fagan et al. 2015; Loening 2015; Lacey 2017).[3] This case has been controversial since the original publication, involving several issues that have been hotly debated in the scientific literature, to which we cannot do justice here. Thus, it is important to bear in mind that we do not wish to address here the merits of the authors' conclusions or their implications for the commercial products under discussion, even though these will be surely aspects considered by the student teams. It is enough to take into account that the story behind the retraction suggests to the students an interplay between values, interests, and scientific research that at least part of them may have ignored until that moment, believing that science is a value-free enterprise. They are straightforwardly questioned about it, when the voter asks whether value judgments are involved in scientists' decisions on what and how to investigate, and people's and organizations' decision on whether and how to use scientific evidence and knowledge. This question is grounded on Lacey's (1999) idea that the choice of research strategy is a key moment in scientific work where values play an important role in shaping whether and how scientists will tackle an issue.

The simple fact that, in the retraction announcement, the Editor-in-Chief of *Food and Chemical Toxicology* states that "… the results presented (while not incorrect) are inconclusive" and that he "found no evidence of fraud or intentional misrepresentation of the data" indicates what kinds of reflection the case can raise among the

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[3] For comments by Séralini and his team, see Séralini et al. (2013, 2014b, c). Several letters questioning the original study by Séralini et al. can be found in *Food and Chemical Toxicology*. The retraction note is found in FCT (2014). See also Hayes (2014).

students, to say the least about peer-reviewing as a critical foundation of scientific inquiry and its relation to issues such as the objectivity of research (despite its value-laden nature). As they find and read through the literature surrounding the Séralini case, they will delve into several interesting discussions related to epistemological and STS aspects. Moreover, their previous judgments about transgenics, their impacts, and their regulation are likely to be challenged, perhaps modified, and probably strengthened, as they consider different sides of these issues they may have neglected before. The guiding questions are shown in Table 26.2.

Along the semesters we have been using this SSI, our teachers' diaries show that the student teams often find the paper by Séralini and colleagues before this part. Usually, half of the teams discover that the paper has been retracted, and, for this reason, they do not take it into consideration in their decision-making. Half of the teams take the paper into account, but as they survey and read several works, some supporting, some denying risks for health resulting from transgenic food, this particular paper becomes one among several they have to consider. This is an interesting outcome since it may allow them to learn that no single work is a decisive, crucial piece in the acceptance of a scientific claim.

When the students discover that the Séralini paper has been retracted, they are stimulated by the tutors to read the letters, editorial, and papers about the case, and this helps them discuss the role of values and interests in scientific research. The expectation is that they identify values involved in the positions taken by both scientists and activists, underlying the differences in perspectives found in the documents originally provided by the deputies' assistants. We provoke also a discussion on where values interfere in research: in the choice of study goals, in methodological decisions, in the conclusions drawn from the data, in the use of research outcomes in society, etc. Finally, they typically find it difficult to discuss the relationships between value issues and the objectivity of science because they need first to reach an agreement on what the word "objectivity" means. As usual along the teaching approach, they are stimulated to do brainstorming and later look for materials to read and socialize their views in team discussion. They end up appealing to the ideas that objectivity means either impartiality or neutrality and/or that objective knowledge reflects more the world than the scientists' subjective opinions. We tackle these ideas later in the systematizing lectures.

We reproduce below a passage from a student team's problem-solving report to illustrate how they argue about the Séralini case:

> … even though this paper [Serálini et al.] had an influence, we cannot make a decision informed by scientific knowledge from one single study – we should do a systematic and comprehensive search in order to find an amount of studies representing the available scientific knowledge (Meline 2006). A study is evaluated alongside others in order to weigh favorable and non favorable evidence towards a certain issue and is evaluated in relation to possible biases in data interpretation. This work has been widely publicized by the media in a diversity of ways. The selection of one or more studies for publicizing in the media (…) is not structured in this way, and thus scientific knowledge is not represented in a comprehensive manner. This partiality may have been created intentionally, as a ground for reinforcing a pre-established perspective; or non intentionally due to media producers' lack of knowledge about methodologies for searching and evaluating scientific literature. (…).

> Besides scientific papers, our decision was also influenced by ethical principles. The precautionary principle is understood as a preference to cautious measures when facing situations where an activity has the potential to be detrimental to human well-being or the environment, even when there are no sound conclusions regarding the real risk of the activity (Kriebel et al. 2001). Adopting the precautionary principle in this case, in which there is so much uncertainty involving the possible effects of transgenic food on the human body, we are against the removal of the label indicating the presence of transgenics. We emphasize that the removal of the label is a violation of consumer's right. (…). We believe the consumer has the right to be aware of what she is consuming and to exert her freedom of choice about consuming or not.

Along the work of the student teams with the SSI, the tutors and teachers occasionally help, but only with metacognitive questions, as the problem-solving activity should be performed by the students and the problems should remain ill-structured.

As it is unlikely that the students will be able to raise and systematize all the relevant NOS features related to each problem on their own, particularly within the constraints of classroom time, we use systematizing classes after each SSI to support students' systematic understanding of the topics at issue. We think it is crucial, however, that explicit teaching only takes place after the students explored the topics in small groups and also that they search, select, and read materials by themselves before receiving selected readings and expositions from the teacher.

In the undergraduate course, the topics covered in the systematizing lectures comprise, for instance, rationality, evidence, and methods; hypothesis testing and confirmation; scientific theories and explanations; models and their relation with reality and theories; the role of models in the construction and progress of scientific knowledge and in decision-making in socioecological systems; and science, values, politics, and research and development (R&D) funding.

26.4.4 Exemplifying the PBL Participatory Approach to Teaching About NOS in a Graduate Setting

In the Professional Master course, we also have a set of problems ready to use. They are also SSI, but from a particular nature: they are problems embedded into the kind of environmental decision-making experience our students face in a daily basis. One of these problems, for example, concerns a requirement by an NGO that the Brazilian Public Ministry[4] initiate a public civil action against a shrimp farm and a state environmental agency. The scenario is set by a text presenting an argument to the effect that the farm is not complying with four prescriptions of the Brazilian Environmental Act and, despite that, the environmental agency has not taken the

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[4] The Brazilian Public Ministry is a federal or state organ responsible for representing and safeguarding the interests of society by investigating criminal facts denounced by citizens or organizations, for protecting victims and witnesses, and for carrying out public action against the investigated crimes.

Table 26.3 Example of socioscientific issue, problems, and guiding questions used in participatory PBL learning at a Professional Master graduate course on introduction to scientific knowledge. We skip Parts 3 and 4 because they concern another course offered together with the course at stake

Socioscientific issue: As environmental technicians from the Brazilian Public Ministry, the students should make decisions on an NGO requirement that this organization initiates a public civil action against a shrimp farm that disobeyed the Brazilian Environmental Act and a state environmental agency that did not take the needed controlling measures.

Parts	Problems	Guiding questions
1	You should critically assess the arguments that the NGO presents to the effect that the shrimp farm disobeyed the Brazilian Environmental Act and the state environmental agency failed in executing the proper controlling measures, based on the evidence available in the text	1. Detect the pieces of evidence used by the NGO to conclude that both the shrimp farm and the environmental agency failed to comply with the legislation 2. Classify the pieces of evidence based on their reliability 3. Critically appraise the arguments posed by the NGO
2	You should seek additional information/knowledge/evidence to evaluate the arguments, making your own searches for new materials	1. Search for additional information/knowledge/evidence to evaluate the arguments provided by the NGO 2. Classify the sources of each new piece of information/knowledge/evidence based on their reliability 3. Improve the critical appraisal of the NGO arguments
5	You should prepare a relevant document concerning the impact of shrimp farms on an estuarine ecosystem	1. Decide about the kind of document you want to elaborate 2. Offer a justification for the relevance of the document 3. Elaborate the document

Source: Elaborated by the authors

proper controlling measures. Four increasingly challenging problems are presented to the student teams, each intended to contribute to improve their abilities to gather and use reliable knowledge (especially, scientific) to evaluate and produce sound arguments in the decision-making process. The students play the role of environmental technicians working in the Brazilian Public Ministry (Table 26.3). We illustrate in Table 26.4 how we use learning outcomes planned for each problem to support instructors' interventions during classroom work.

The first problem relies only on the students' previous knowledge. They need to critically assess the arguments from the NGO based on the evidence presented in the text. The guiding questions indicate that they need to detect and classify the evidence based on reliability and, from such classification, evaluate how sound are the arguments. The NGO document presents pieces of evidence sustained by sources of different levels of reliability, such as peer-reviewed journals, blogs, meeting papers, governmental reports, etc.

Table 26.4 Learning outcomes intended for the first two problems used in the course "introduction to scientific knowledge," from the Professional Master Course in Ecology Applied to Environmental Management. Conceptual, practical, and attitudinal dimensions are conceived from the perspective of the critical and multidimensional approach to contents proposed by Conrado (2017) and Conrado and Nunes-Neto (2018)

Content dimensions	Cognitive skills (from the revised Bloom taxonomy)	Learning outcomes	
		Problem 1	Problem 2
C	*Remember*	That technical conclusions can decisively impact decision-making in applied questions That distinct information can show different degrees of reliability	That there is a huge amount of accumulated knowledge related to any environmental topic
C	*Understand*	That conclusions should be grounded on arguments supported by evidence That the reliability of a conclusion is contingent upon the reliability of arguments and evidence That objective criteria can be used to establish the reliability of evidence and arguments That the scientific tradition is characterized, among other features, by the search for rigorous patterns for evaluating the reliability of evidence and arguments	That it is possible to rescue a relevant portion of accumulated knowledge aiming at better decision-making That peer review is one of the social processes employed by the scientific communities to establish canonical patterns of reliability That the reliability of statements and inferences in an argument may be the focus of specific evaluation That conclusions presented in more qualified scientific sources usually tend to be more reliable
C/P	*Apply*	Criteria for evaluating the reliability of particular pieces of evidence	Criteria for evaluating the reliability of particular sources of evidence
C/P	*Analyze*	The evidence, arguments, and conclusions presented in the hypothetical situation based on reliability criteria	The quality of the sources of information based on reliability criteria
C/P	*Evaluate*	If the report on the hypothetical situation fulfilled the goals leading to its elaboration in a reliable manner	If the report on the hypothetical situation fulfilled the goals leading to its elaboration in a reliable manner

(continued)

Table 26.4 (continued)

Content dimensions	Cognitive skills (from the revised Bloom taxonomy)	Learning outcomes	
		Problem 1	Problem 2
C/P	*Create*	Criteria for evaluating the reliability of evidence, arguments, and conclusions and, based on them, a critical analysis of the report on the hypothetical situation produced by the NGO	A system for classifying the reliability of sources of information
P	–	To develop abilities for teamwork	To develop abilities to rescue relevant and reliable scientific information
A	–	To reflect on how adherence to epistemic values such as rationality and rigor may positively alter the professional practice in the field of environmental management	To reflect on how adhesion to epistemic values such as rationality and rigor may positively alter the professional practice in the field of environmental management, especially with regard to rescuing reliable sources and information

Source: Elaborated by the authors
C conceptual, *P* practical, *A* attitudinal

In the second problem, they are asked to seek additional information or knowledge or evidence[5] to evaluate the arguments, making their own searches. The guiding questions demand that they both perform these searches and classify the obtained information/knowledge/evidence based on reliability. From the appraisal of new materials, they should improve their evaluation of the NGO arguments.

We are creating conditions, thus, to improve the environmental technicians' abilities to search for information and knowledge, more specifically from the scientific literature, and to appraise the quality of the information/knowledge/evidence obtained. Moreover, they also have opportunities to build capacity to integrate scientific knowledge into the environmental decision-making processes in which they are usually engaged but from a critical perspective that allows them to evaluate how reliable is the knowledge they are appealing to.

From our teachers' diaries, we can adduce that both problems have been playing an important role in expanding students' reflection on what makes scientific knowledge reliable, considering the reliability of evidence and the control processes involved in scientific research and publication. They become more capable of appraising reliability by engaging in understanding the differences between, say, papers published in peer-reviewed journals or books and texts found in webpages,

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[5] We do not constrain the search for one of these categories in order to avoid the outcome that the students do more limited searches, say, neglecting the search for evidence instead of conceptual material.

meeting papers, and governmental reports. Surely there is more to appraising reliability than that, but this is a relevant first step for the technicians. They also improve their capacity of appealing to scientific ideas and evidence to increase the strength of their technical arguments.

In the systematizing lectures, we address statistical analysis and knowledge reliability, systematizing ideas about evidence and their role in scientific knowledge production. We also discuss argumentation in science and how to build quality arguments. Another topic is the nature of scientific knowledge and its differences and similarities in relation to other forms of knowledge, particularly practitioner knowledge.

The subsequent problems merge issues related to NOS with a predominant focus on specific questions about scale and system organization, as the course "introduction to scientific knowledge" is combined with a course on biological systems and levels of organization. The students are asked in the third problem to list ecological processes relevant to the hypothetical situation and to evaluate the spatial and temporal scale in which these processes operate, and in the fourth problem they have to build a mechanistic model to explain the phenomena of interest in the situation. We do not detail these problems here, because they fall outside the scope of the chapter.

In the last problem, they are asked to elaborate a relevant document concerning the theme addressed in the hypothetical situation, in the present example, the impact of shrimp farms on an estuarine ecosystem. This document will be the final work of the two courses, which will be graded by the teachers. As the guiding questions state, they should decide about the kind of document they will elaborate (say, a technical report to be used by other managers or technicians, a popular science piece publicizing the environmental problem at stake, a guiding document for local communities to understand the impact of the enterprise on the environment they live, and so forth). Moreover, they need to offer a justification for its relevance, which will be also evaluated. Evaluation also considers whether the document is convincing, in terms of the quality of evidence, arguments, and conclusions, and whether ecological knowledge is aptly included, with proper attention to ecological processes, scales, and organization levels.

Here we reproduce some parts of a document prepared by one of the student teams, which opted for elaborating a technical guideline for environmental decision-making at state or federal agencies. They illustrate how the students are integrating NOS and other aspects addressed in the course in the context of environmental decision-making:

> **Integrity of the Apicum**
>
> *Phenomenon*: Shrimp farming in *apicum* areas interferes with the integrity of the associated mangroves, since it alters the ecological succession needed for their maintenance. (…).
>
> *Inference* (strong): the *apicum* is a hypersaline plain commonly associated with mangroves, flooded by the tide and usually deprived from arboreal vegetation, even though it may show colonization by herbaceous plants. Scholarly studies on coastal environments show that the mangrove ecosystem and the flooded terrains associated with it, such as the *apicum*, are regulated by frequent changes in the topography and configuration of the landscape, and by the advance or retreat of the vegetation. (…) shrimp farming in the *apicum* can hinder the natural expansion of the mangrove, which tends to occupy adjacent areas. Moreover, shrimp ponds alter the natural channels carved by the tide, negatively influencing

> the dynamics of propagule and seed dispersion, altering the natural regeneration of the mangrove.
>
> *Discussion*: (…) the difficulty in the technical analysis for licensing shrimp farming begins in the gap between the environmental legislation (…) and the relevant scientific knowledge. To be convincing to the maximum extent possible, technical decision-making (…) should go beyond the relevant environmental laws. The technical arguments should be grounded on the scientific knowledge and the precautionary principle. The technician should use tools that help understand the importance of ecological processes and environmental services related to the *apicum* and mangroves. (…) Technical practice in environmental management is improved by rigorous searches for the reliability of the arguments and premises, surveys of theoretical frameworks, critical appraisal of the design of the available tests and experiments, and development of theoretical models.

26.5 Concluding Remarks

In this chapter, we described a PBL participatory methodology to teach about NOS. We illustrated this methodology by considering both undergraduate and graduate courses. From both our notes taken along the courses and the works delivered by the students (from which some passages were quoted above), we can see that students' engagement and learning increased, in comparison to other approaches we previously used. Moreover, this engagement has been translated into investment in reading and analyzing relevant material that was put to work in problem-solving and decision-making by the students themselves.

At least 70% of the undergraduate students and virtually every Professional Master student who attended the courses reported to us his or her satisfaction with the PBL approach. As this approach is used throughout the Professional Master program, an overall survey of students' satisfaction with PBL was made for all courses. The data from this survey indicate that the students are highly satisfied with the use of PBL and consider the approach adequate for fulfilling the intended educational goals, for developing ecological knowledge, and for developing fruitful attitudes and practices in their work.

Overall, we are satisfied as teachers with the PBL participatory approach, as the students have been engaging in the challenging subjects covered when we teach about NOS much more than in any other previous experiences we had. We always faced great difficulty to engage students in reading the text assignments. However, with this approach, we notice every semester that most of the students engage in surveying and reading relevant material, including epistemological, sociological, ethical, and scientific materials, and manage to put the readings to work in developing arguments exposed in their problem-solving reports.

Argumentative capacity has been shown by most student teams in their problem-solving reports, and improvement of the reports along the semester indicates that learning on how to properly argue has been also taking place. This is not to say there are no mistakes or unclear ideas in the reports, or that they do not make use of flawed or superficial arguments at some points, but that they acquire – at least to some extent – skills to argue and to dialogue with the relevant literature.

Particularly in the undergraduate course, students' dropout rates decreased after we implemented this approach. Dropout was a problem before, particularly when the course was very demanding in reading assignments. This is yet another reason for our satisfaction with the PBL participatory approach.

It is worth stressing that the PBL approach we use includes a considerable level of guidance to the students. That's why we call it participatory PBL, since it is not just student-centered, as it is common in active methodologies, but also involves a substantial amount of teachers' mediation of the students' relation with knowledge.

In both the undergraduate and graduate courses, we explicitly focus on NOS contents, either in problem-solving activities or in the lectures. After all, explicit approaches have been shown to be more effective than implicit ones in teaching about NOS (e.g., Abd-El-Khalick and Lederman 2000). In the lectures, we address the NOS contents that appear in the problem-solving activities, highlighting aspects in which the students put into action knowledge that is aligned with what is generally accepted in HPSS and explicitly considering limits in their arguments that depart from generally accepted ideas. In many cases, evidently, the instructors need to introduce other perspectives on NOS aspects that the students did not consider, given the multiple views and controversies regarding several of these aspects, but this is done always in relation to what the students developed in their problem-solving reports.

Surely, there are limits to the teaching approach described here. For instance, every semester we observe students' uneven engagement, which can be particularly harmful for teamwork. Less engagement is usually correlated with less satisfaction with the approach, as expected. Another important constraint is the time-consuming task of reading and evaluating the problem-solving reports, which delays feedback to the students. We also suffer from the lack of PBL-friendly classrooms at our university, where most rooms are planned for lectures only, making it likely that student teams interfere with the work of one another. Moreover, at least concerning the undergraduate course, a difficulty to obtain better results follows from the fact that the students have only limited experience with active/participatory methods in their educational lives. This makes it harder to foster the understanding that they are really responsible for their own learning, that they should not just passively listen to the teacher, but actively search for knowledge and develop apt attitudes and practices. In some way, their mental models of teaching and learning, as far as they are quite influenced by the lecture-based, passive methods they experienced in most of their schooling, constitute an important obstacle to overcome in order to successfully apply any active/participatory method. In order to overcome this, we think, it is important to try to implement more radical changes in the curriculum as a whole, implementing active/participatory strategies to a larger extent.

References

Abd-El-Khalick, F., & Lederman, N. G. (2000). Improving science teachers' conceptions of nature of science: A critical review of the literature. *International Journal of Science Education, 22*, 665–701.

Albanese, M. A., & Dast, L. (2014). Problem-based learning: Outcomes evidence from the health professions. *Journal on Excellence in College Teaching, 25*, 239–252.

Albanese, M. A., & Mitchell, S. (1993). Problem-based learning: A review of literature on its outcomes and implementation issues. *Academic Medicine, 68*, 52–81.

Alfieri, L., Brooks, P. J., Aldrich, N. J., & Tenenbaum, H. R. (2011). Does discovery-based instruction enhance learning? *Journal of Educational Psychology, 103*, 1–18.

Allchin, D. (2011). Evaluating knowledge of the nature of (whole) science. *Science Education, 95*, 518–542.

Ames, C. (1992). Classrooms: Goals, structures, and student motivation. *Journal of Educational Psychology, 84*, 261–271.

Araujo, J. C. S. (2017). Da metodologia ativa à metodologia participativa. In I. P. A. Veiga (Org.), *Metodologia participativa e as técnicas de ensino e aprendizagem* (pp. 9–46). Curitiba: Editora CRV.

Barker, G., & Kitcher, P. (2013). *Philosophy of science: An introduction*. New York: Oxford University Press.

Barrows, H. S. (1996). Problem-based learning in medicine and beyond: A brief overview. *New Directions for Teaching and Learning, 68*, 3–12.

Barrows, H. S. (2002). Is it truly possible to have such a thing as dPBL? *Distance Education, 23*, 119–122.

Batdi, V. (2014). The effects of a problem-based learning approach on students' attitude levels: A meta-analysis. *Educational Research and Reviews, 9*, 272–276.

Blackburn, S. (2008). *The Oxford dictionary of philosophy* (2nd ed.). Oxford: Oxford University Press.

Carvalho, I. N., Conrado, D. M., El-Hani, C. N., & Nunes-Neto, N. F. (2018). Transgênicos, leis e a ciência: trazendo a legislação para a sala de aula de biologia. In N. F. Nunes-Neto, & D. M. Conrado (Orgs.), *Questões sociocientíficas: fundamentos, propostas de ensino e perspectivas* (pp. 277–302). Salvador: EDUFBA.

Chevallard, Y. (1989). On didactic transposition theory: Some introductory notes. In *Proceedings of the international symposium on selected domains of research and development in mathematics education* (pp. 51–62). http://yves.chevallard.free.fr/spip/spip/article.php3?id_article=122. Accessed 19 Nov 2018.

Coll, C., Pozo, J. I., Sarabia, B., & Valls, E. (1992). *Los contenidos de la reforma: enseñanza y aprendizaje de conceptos, procedimientos y actitudes*. Buenos Aires: Ediciones Santillana.

Colliver, J. A. (2000). Effectiveness of problem-based learning curricula: Research and theory. *Academic Medicine, 75*, 259–266.

Conrado, D. M. (2017). *Questões sociocientíficas na educação CTSA: contribuições de um modelo teórico para o letramento científico crítico*. PhD dissertation. Salvador: Graduate Studies Program in History, Philosophy and Science Teaching, Federal University of Bahia and State University of Feira de Santana.

Conrado, D. M., & Nunes-Neto, N. F. (Orgs.). (2018). *Questões sociocientíficas: fundamentos, propostas de ensino e perspectivas para ações sociopolíticas*. Salvador: EDUFBA.

Conrado, D. M., Viana, B. F., Schadelbach, A. S., Nunes-Neto, N. F., & El-Hani, C. N. (2016). Socioscientific issues about bees, pollination and food production in biology teaching. In *Proceedings of the 11th conference of the European Science Education Research Association (ESERA)*. Helsinki: ESERA.

Conrado, D. M., Nunes-Neto, N. F., & El-Hani, C. N. (In press). Como abordar questões sociocientíficas na sala de aula: A estratégia didática de cinco fases para o ensino de ciências. *Indagatio Didactica*.

Daston, L., & Galison, P. (2007). *Objectivity*. Brooklyn: Zone Books.

Dochy, F., Segers, M., Van den Bossche, P., & Gijbels, D. (2003). Effects of problem-based learning: A meta-analysis. *Learning and Instruction, 13*, 533–568.

Duschl, R. A., & Grandy, R. (2013). Two views about explicitly teaching Nature of Science. *Science & Education, 22*, 2109–2139.

El-Hani, C. N. (2006). Notas sobre o ensino de história e filosofia das ciências na educação científica de nível superior. In C. C. Silva, C. C. (Org.). *História e Filosofia da Ciência no Ensino de Ciências: da teoria à sala de aula* (pp. 3–21). São Paulo: Editora Livraria da Física.

El-Hani, C. N. (2007). Notas sobre o ensino de história e filosofia da biologia na educação superior. In R. Nardi (Org.), *A pesquisa em Ensino de Ciências no Brasil* (pp. 293–315). São Paulo: Escrituras.

El-Hani, C. N., Tavares, E. J. M., & Rocha, P. L. B. (2004). Concepções epistemológicas de estudantes de Biologia e sua transformação por uma proposta explícita de ensino sobre história e filosofia das ciências. *Investigações em Ensino de Ciências, 9*, 265–313.

Erduran, S., & Dagher, Z. (2014). *Reconceptualizing the nature of science in science education*. Dordrecht: Springer.

Fagan, J., Traavik, T., & Bohn, T. (2015). The Séralini affair: Degeneration of science to re-Science? *Environmental Sciences Europe, 27*, 19.

FCT (Food and Chemical Toxicology). (2014). Retraction notice to 'Long-term toxicity of a roundup herbicide and a roundup-tolerant genetically modified maize'. *Food and Chemical Toxicology, 63*, 244.

Fellet, M. (2018). *Strategies for science communication in a post-factual era*. Lindau Nobel Laureate Meetings. https://www.lindau-nobel.org/de/blog-strategies-for-science-communication-in-a-post-factual-era/. Accessed 1 Nov 2018.

Gijbels, D., Dochy, F., Van den Bossche, P., & Segers, M. (2005). Effects of problem-based learning: A meta-analysis from the angle of assessment. *Review of Educational Research, 75*, 27–61.

Gijselaers, W. (1995). Perspectives on problem-based learning. In W. Gijselaers, D. Tempelaar, P. Keizer, J. Blommaert, E. Bernard, & H. Kapser (Eds.), *Educational innovation in economics and business administration: The case of problem-based learning* (pp. 39–52). Dordrecht: Kluwer.

Godfrey-Smith, P. (2003). *Theory and reality: An introduction to the philosophy of science*. Chicago/London: The University of Chicago Press.

Greenpeace. (2011). *Environmental and health impacts of GM crops – the science*. https://www.greenpeace.org/archive-eu-unit/Global/eu-unit/reports-briefings/2011%20pubs/9/Health%20and%20Environmental%20Impacts%20of%20GM%20crops.pdf. Accessed 1 Nov 2018.

Hayes, A. W. (2014). Editor in Chief of Food and Chemical Toxicology answers questions on retraction. *Food and Chemical Toxicology, 65*, 394–395.

Hmelo-Silver, C. E. (2012). International perspectives on problem-based learning: Contexts, cultures, challenges, and adaptations. *Interdisciplinary Journal of Problem-Based Learning, 6*, 10–17.

Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2007). Scaffolding and achievement in problem-based and inquiry learning: A response to Kirschner, Sweller, and Clark (2006). *Educational Psychologist, 42*, 99–107.

Hodson, D. (2014). Nature of science in the science curriculum: Origin, development, implications and shifting emphases. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 911–970). Dordrecht: Springer.

Irzik, G., & Nola, R. (2011). A family resemblance approach to the nature of science for science education. *Science & Education, 20*, 591–607.

Kampourakis, K. (2016). The "general aspects" conceptualization as a pragmatic and effective means to introducing students to Nature of Science. *Journal of Research in Science Teaching, 53*, 667–682.

Kelly, T. (2016). Evidence. In E. N. Zalta (Ed.), *The Stanford encyclopedia of philosophy* (Winter 2016 ed.). https://plato.stanford.edu/archives/win2016/entries/evidence/. Accessed 1 Nov 2018.

Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist, 41*, 75–86.

Kitcher, P. (2001). *Science, truth and democracy*. Oxford: Oxford University Press.

Krathwohl, D. R. (2002). A revision of Bloom's taxonomy: An overview. *Theory Into Practice, 41*, 212–218.

Kriebel, D., Tickner, J., Epstein, P., Lemons, J., Levins, R., Loechler, E. L., Quinn, M., Rudel, R., Schettler, T., & Stoto, M. (2001). The precautionary principle in environmental science. *Environmental Health Perspectives, 109*, 871–876.

Lacey, H. (1999). *Is science value-free? Values and scientific understanding*. London: Routledge.

Lacey, H. (2017). The safety of using genetically engineered organisms: Empirical evidence and value judgments. *Public Affairs Quarterly, 31*, 261–281.

Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., & Schwartz, R. S. (2002). Views of nature of science questionnaire (VNOS): Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching, 39*, 497–521.

Levinson, R. (2006). Towards a theoretical framework for teaching controversial socio-scientific issues. *International Journal of Science Education, 28*, 1201–1224.

Lewinsohn, T. M., Attayde, J. L., Fonseca, C. R., Ganade, G., Jorge, L. R., Kollmann, J., Overbeck, G. E., Prado, P. I., Pillar, V. D., Popp, D., Rocha, P. L. B., Silva, W. R., Spiekermann, A., & Weisser, W. W. (2015). Ecological literacy and beyond: Problem-based learning for future professionals. *Ambio, 44*, 154–162.

Loening, U. E. (2015). A challenge to scientific integrity: A critique of the critics of the GMO rat study conducted by Gilles-Eric Séralini et al. (2012). *Environmental Sciences Europe, 27*, 13.

Matthews, M. R. (2012). Changing the focus: From nature of science (NOS) to features of science (FOS). In M. S. Khine (Ed.), *Advances in nature of science research: Concepts and methodologies* (pp. 3–26). Dordrecht: Springer.

Maurer, H., & Neuhold, C. (2012). Problems everywhere? Strengths and challenges of a problem-based learning approach in European studies. In *Higher education academy social science conference "Ways of knowing, ways of learning"*. York: Higher Education Academy.

Mayo, D. G. (1996). *Error and the growth of experimental knowledge*. Chicago: The University of Chicago Press.

McComas, W. F. (1998). The principal elements of the nature of science: Dispelling the myths. In W. F. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 41–52). Dordrecht: Kluwer.

McComas, W. F. (2019). Principal elements of NOS: Informing science teaching while dispelling the myths. In W. F. McComas (Ed.), *The nature of science in science instruction: Rationales and strategies*. Dordrecht: Springer.

Meline, T. (2006). Selecting studies for systematic review: Inclusion and exclusion criteria. *Contemporary Issues in Communication Science and Disorders, 33*, 21–27.

National Academy of Sciences U.S. (NAS). (2016). *Genetically engineered crops: Experiences and prospects*. Washington, DC: National Academy Press. https://www.nap.edu/catalog/23395/genetically-engineered-crops-experiences-and-prospects. Accessed 1 Nov 2018.

Neville, A. J. (2009). Problem-based learning and medical education forty years on: A review of its effects on knowledge and clinical performance. *Medical Principles and Practice, 18*, 1–9.

Niaz, M. (2009). *Critical appraisal of physical science as a human enterprise: Dynamics of scientific progress*. Dordrecht: Springer.

Pardini, R., Rocha, P. L. B., El-Hani, C. N., & Pardini, F. (2013). Challenges and opportunities for bridging the research-implementation gap in ecological science and management in Brazil. In P. Raven, N. S. Sodhi, & L. Gibson (Eds.), *Conservation Biology: Voices from the tropics* (pp. 75–85). Oxford: Wiley.

Pintrich, P. R. (1989). The dynamic interplay of student motivation and cognition in the college classroom. In C. Ames & M. Maehr (Eds.), *Advances in motivation and achievement: Motivation-enhancing environments* (Vol. 6, pp. 117–160). Greenwich: JAI Press.

Pintrich, P. R., Marx, R. W., & Boyle, R. A. (1993). Beyond cold conceptual change: The role of motivational beliefs and classroom contextual factors in the process of conceptual change. *Review of Educational Research, 63*, 167–199.

Portier, C. J., Goldman, L. R., & Goldstein, B. D. (2014). Inconclusive findings: Now you see them, now you don't! *Environmental Health Perspectives, 122*, A36.

Ryan, R., Connell, J., & Deci, E. (1985). A motivational analysis of self-determination and self-regulation in education. In C. Ames & R. Ames (Eds.), *Research on motivation in education* (Vol. 2, pp. 13–51). New York: Academic Press.

Sadler, T. D. (2004). Moral and ethical dimensions of socioscientific decision-making as integral components of science literacy. *Science Educator, 13*, 39–48.

Savery, J. R. (2006). Overview of problem-based learning: Definitions and distinctions. *The Interdisciplinary Journal of Problem-based Learning, 1*, 9–20.

Scholz, R. W. (2017). The normative dimension in transdisciplinarity, transition management, and transformation sciences: New roles of science and universities in sustainable transitioning. *Sustainability, 9*, 991.

Séralini, G. E., Clair, E., Mesnage, R., Gress, S., Defarge, N., Malatesta, M., Hennequin, D., & de Vendômois, J. S. (2012). Retracted: Long-term toxicity of a Roundup© herbicide and a Roundup©-tolerant genetically modified maize. *Food and Chemical Toxicology, 50*, 4221–4331.

Séralini, G.-E., Clair, E., Mesnage, R., Gress, S., Defarge, N., Malatesta, M., Hennequin, D., & de Vendômois, J. S. (2013). Answers to critics: Why there is long term toxicity due to roundup-tolerant genetically modified maize and to a Roundup herbicide. *Food and Chemical Toxicology, 53*, 476–483.

Séralini, G.-E., Clair, E., Mesnage, R., Gress, S., Defarge, N., Malatesta, M., Hennequin, D., & de Vendômois, J. S. (2014a). Republished: Long-term toxicity of a Roundup© herbicide and a Roundup©-tolerant genetically modified maize. *Environmental Sciences Europe, 26*, 14.

Séralini, G.-E., Mesnage, R., Defarge, N., & de Vendômois, J. S. (2014b). Conclusiveness of toxicity data and double standards. *Food and Chemical Toxicology, 69*, 357–359.

Séralini, G.-E., Mesnage, R., Defarge, N., & de Vendômois, J. S. (2014c). Conflicts of interests, confidentiality and censorship in health risk assessment: The example of an herbicide and a GMO. *Environmental Sciences Europe, 26*, 13.

Shin, I.-S., & Kim, J.-H. (2013). The effect of problem-based learning in nursing education*: A meta-analysis*. *Advances in Health Sciences Education, 18*, 1103–1120.

Strobel, J., & van Barneveld, A. (2009). When is PBL more effective? A meta-synthesis of meta-analyses comparing PBL to conventional classrooms. *The Interdisciplinary Journal of Problem-Based Learning, 3*, 44–58.

Sweller, J., Kirschner, P. A., & Clark, R. E. (2007). Why minimally guided teaching techniques do not work: A reply to commentaries. *Educational Psychologist, 42*, 115–121.

Toulmin, S. (2003). *The uses of argumentation*. New York: Cambridge University Press.

Tress, B., Tress, G., & Fry, G. (2005). Defining concepts and the process of knowledge production in integrative research. In B. Tress, G. Tress, G. Fry, & P. Opdam (Eds.), *From landscape research to landscape planning: Aspects of integration, education and application* (pp. 13–26). Dordrecht: Springer.

Zeidler, D. L., Sadler, T. D., Simmons, M. L., & Howes, E. V. (2005). Beyond STS: A research-based framework for socioscientific issues education. *Science Education, 89*, 357–377.

Chapter 27
Storytelling as a Pedagogical Tool in Nature of Science Instruction

Nausica Kapsala and Evangelia Mavrikaki

27.1 Introduction

Nature of science (NOS), the field that describes what science is, how it works, and its bidirectional interactions with society from the perspectives of philosophy, history, sociology, and psychology of science (McComas et al. 1998), is considered an essential aspect of science literacy (Allchin 2014; DeBoer 1991). However, the incorporation of NOS into school practice is challenging. Teachers tend to underestimate the significance of NOS and mostly focus on traditional science content. When educators do attempt to approach NOS, they encounter difficulties due to the pressures of time, lack of resources, and even their own (mis)understanding of NOS (Abd-El-Khalick et al. 1998; Höttecke and Silva 2011), unless they are provided with sufficient support and teaching materials (Ratcliffe and Millar 2009).

We suggest that telling stories derived from the History of Science (HOS) could be one useful pedagogical tool for teaching NOS aspects; doing so could enable teachers to overcome the abovementioned obstacles. By "NOS aspects" we mean those that guide this book and can be grouped in three core concepts: special nature of scientific knowledge, tools and products of science, and human aspects of science.

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_27

27.1.1 Storytelling as a Teaching Method

Storytelling has been a universal successful teaching and learning method ever since humans started to communicate through speech (Egan 1989), yet it remains intertemporal and modern (Bruner 2003). Stories constitute a strong mnemonic tool (Egan 1989) mainly due to two characteristics: (a) their form (Klassen 2006; Bruner 1985) and (b) the fact that they provoke emotions and feelings (Egan 1989).

However, there is another reason why stories enchant us, captivate our interest, and help us learn, and this is just human nature. *Homo sapiens* has evolved communicating through stories (Cron 2012; Gottschall 2012). The storytelling ability constitutes an evolutionary survival advantage which turns out to be represented in the neural circuitry of the human brain (Nigam 2012). Neurobiological studies have revealed that when listening to a story, dopamine is released to the brain, indicating storytelling's evolutionary significance (Boyd 2009). As the story unfolds, and the action rises, our brain gives the signals for the production of cortisol – that keeps it alert – and oxytocin that promotes connection and empathy (Zak 2015). While we are being absorbed in a narrative, mirror neurons get activated in several parts of the brain, including motor areas, as if we were experiencing the story firsthand (Cheetham et al. 2014; Speer et al. 2009).

All the above indicate that storytelling can be a useful pedagogical tool. As storytelling lies in the human nature, all humans, especially teachers can tell stories, and they often do, even without realizing it. When storytelling is used in class, it reinforces class cohesion, and the relationships among students and between students and the teacher (Wills 1992), as it helps them to understand each other (Abrahamson 1998). Students and teachers get satisfied, inspired (Klassen and Klassen 2014), and motivated to act (Kokkotas et al. 2010). Furthermore, imagination is cultivated, and *mental images* are being formed (Hadzigeorgiou et al. 2011). Furthermore, storytelling, alongside with drama and role-play activities, may as well be the only ways to achieve "experiential learning" when hands-on learning comes to be too dangerous or even impossible (Hadzigeorgiou et al. 2011).

According to *Kolb's learning cycle*, deep learning is the result of a sequence of experience, reflection, abstraction, and active experimentation (Kolb 2014). This cycle of learning has been neurobiologically explained and results in actual changes in the brain attributed to learning (Zull 2002). Storytelling activates this cognitive cycle and thus leads to deep learning. When reading or listening to a story, the sensory organs receive information (experience). The new information gets linked to previous experience or knowledge since in a story there always are points with which we can connect (reflection); related stories are reflected and linked to the memory's information. The next step is the formation of hypotheses or data management to create new cognitive arrangements (abstraction). There follows action, discussion in class, writing, etc., to test hypotheses (active experimentation), the results of which give feedback to the cycle (Clair 2008). Indeed, research data indicate storytelling is effective as a mean to convey complex scientific information (Csikar and Stefaniak 2018) and that students develop deeper understanding of content knowledge when storytelling is included as part of the instruction (Cross 2017).

27.1.2 *Telling Stories from the HOS Promotes NOS Understanding*

The value of the *history of science (HOS)* in teaching NOS has been repeatedly acknowledged (McComas 2015; Matthews 1994; Klopfer 1969), since a historical perspective puts science into context (Galili 2015; Klassen 2006) and illuminates NOS aspects such as the special nature of scientific knowledge, and its *tentative*, yet durable, character, as well as science's tools, like the nature of scientific *method* (Eichman 1996), and the fact that not all scientists follow the same procedure to reach scientific knowledge. Moreover, such a historically based approach allows students to "experience science in the making" (Dolphin et al. 2018) and can contribute to better addressing students' alternative ideas (Galili 2015). Through the HOS, science can get humanized, as the human elements in science are emphasized (Hadzigeorgiou 2005). That way, science learning retrieves its meaning as it gets connected to more personal, moral, cultural, and political worries (Matthews 1992).

Different historical vignettes/cases may be found to illuminate different NOS aspects (McComas and Kampourakis 2015; Clough 2011). We propose that such historical cases should be introduced in class by storytelling. By the term "*storytelling*," we mean the act of someone – the science teacher in our case – telling a story orally, live, in his/her own words. Such an act guarantees successful communication between the teller and the listeners, as their brains synchronize (Stephens et al. 2010; Wilson et al. 2008), which is more than wanted in class.

The teaching method of storytelling enforces *critical thought* and promotes understanding facts and the detection of valid and invalid generalizations – both individually when each student compares what he/she knows to the facts of the stories and collectively during the discussion that follows the storytelling. It also helps to focus on concepts and consequences in a moral and distant way (Wills 1992). Telling stories derived from the HOS results in the expansion of science teaching in historical, social, and cultural paths. Thus, links between historical–social conditions, events, and scientific theories are inevitably created. Making such connections and realizing the analogies of today, students have the opportunity to become conscious and be motivated and driven into action for the benefit of the wider society (Engestrom 1999; Lankshear and Mclaren 1993).

27.2 How to Tell an Effective HOS Story[1]

27.2.1 *Choosing and Adapting the Proper Story to Tell*

The *HOS* is full of wonderful stories of achievements, endeavors, and mistakes, which have a lot to teach us about the NOS (McComas 2008) (see also Chaps. 30 and 32). Some web sources describing stories derived from the HOS can be found

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[1] The story-organizing and storytelling tips are derived from personal notes from storytelling workshops with the storytellers: Eleni Achileos, Michael Harvey, Manya Maratou, Anthi Thanou,

Table 27.1 Sources on the web for stories derived from the HOS

Title	Coordinator	Site
Storytelling @ Teaching Model (s@tm)	Panos Kokkotas	http://science-story-telling.eu/
History and Philosophy in Science Teaching (HIPST)	Dietmar Höttecke	http://hipstwiki.wikifoundry.com/page/hipst+developed+cases
Sociology, History, and Philosophy of Science (SHiPS)	Douglas Allchin	http://www.shipseducation.net/
Doing Biology (SHiPS)	Joel Hagen, Douglas Allchin & Fred Singer	http://doingbiology.net/
The Story Behind The Science	Michael P. Clough	http://www.storybehindthescience.org/index.html
National Center for Case Study Teaching in Science (NCCSTS)	Clyde Freeman Herreid	http://sciencecases.lib.buffalo.edu/cs/
Historical Case Studies	Glenn Dolphin	https://geoscience.ucalgary.ca/tamaratt-chair/historical-case-studies
World History of Science Online		http://www.dhst-whso.org/

in Table 27.1 – of course, the table is not complete but indicative. Once a teacher decides to tell a HOS story, he/she must first adapt it to make it suitable for storytelling and for teaching NOS.

The first reason for a story to be chosen is teacher's personal taste. You have to like a story in order to tell it nicely. You have to love it to tell it thrillingly. However, it should be a story that fits into the curriculum. What should be considered next is the purpose of telling that story and the pedagogical goals of the instruction, as they will importantly influence the story's structure and content. What else should be examined is why students would want to listen to that story and how they could connect to it. The answer to the above will also affect the form, the content, and the atmosphere of the story. For example, *The Double Helix* (see Appendix) was considered as the story of two colleagues who chased their dream, going against many of the norms of their time, failing, and trying again, even getting out of the line sometimes, not giving up until they had achieved their goal (Mavrikaki and Kapsala 2012). A story such as this should appeal to anyone – particularly teenagers will want to hear as it is about hopes and dreams that they also have.

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and Sylvia Venizelea. More information can be found in Scheub (1998), Kouloumbi-Papapetropoulou (1997), and Papaliou (1996).

27.2.1.1 Characteristics of a Science Story

For an account of some personalities or discovery in science to be a “story,” it should consist of the following elements, characters, actions, situations, and consequential coherence, and it should be clear about the time that it takes place, either in the past or today, if it refers to an account of science as it occurs. Moreover, it should have a defined plot structure, and at some point, there should be a critical choice made by the hero. Plus, for a story to be a “science story,” it should have scientific concepts and NOS content (Klassen and Klassen 2014).

For the story to be vivid, it should not be full of information, chronologies, and names, but it should have a rich plot that shall contain the events that refer to *what has happened:* actions that reveal the information and values in an interesting way.

27.2.1.2 The Form of the Story

Bruner (2003) reminds us that there is a well-conserved form that all stories share. Stories contain a universal cultural element that reflects a basic, strong structure with which we perceive the world and our experiences (Egan 1986). This narrative form enhances the consistency and *long-term memory*, and it provides us with a structure to which we can organize any related knowledge and experiences (Klassen 2006).

The basic *story structure* can be summarized as follows and can serve as the plot structure of a story (Bruner 2003). It can describe the simplest story and can be repeated several times in a bigger story.

- A regular situation is presented.
- Regularity breaks down (twist).
- A “crisis” follows that includes actions toward overcoming the consequent problems of the twist.
- Regularity is restored, or a revolutionary change happens that introduces a new order of regularity.
- (Optional) Epilogue: a final conclusion that may give new perspectives to the analysis of the story.

Moreover, to organize the story, Rudyard Kipling’s (1902) quote could prove helpful as these are the questions to be answered:

I keep six honest serving men
(They taught me all I knew);
Their names are What and Why and When
And How and Where and Who.

In the beginning of the story, you should present the initial situation; time and place are set along with the scenery in which the story will unfold. The questions *When* and *Where* are answered. Here comes an opportunity to present the *historical,* *cultural, and social factors* that may influence the practice and direction of science later in the story and to introduce students to the conceptual framework of the story's time, which is crucial for their understanding and judgment of the scientists' thoughts, decisions, and actions (Abd-El-Khalick and Lederman 2000b).

Then you should present the hero of the story. *Who?* There can't be a story without a hero, someone with whom the teller and the listeners may identify with, and empathize, or someone they will strongly dislike. The hero of the story could be a scientist, giving later the opportunity to illuminate the human elements of science, *creativity*, *subjectivity*, his/her influences, etc.

After the introduction, the action begins, as one day something different happens, the regularity somehow breaks down, and the hero reacts to that change. *What* and *How* get answered. The story must be consistent and easy for the listeners to follow, but not flat; the flow of the story could be imagined like a cardiogram, with twists and swifts that affect the heroes' routes and feelings.

27.2.1.3 Points for Attention

When intending to bring a science story to the class, there are a few points that should be taken into consideration. First, the historical sources must be authentic and valid (Cohen 1993), and the scientific data must be presented accurately and carefully so that no misunderstandings or misconceptions are introduced. Moreover, as mentioned before, it should be assured that the scientific observations and conclusions are examined in accordance with the conceptual framework of the historical era (Abd-El-Khalick and Lederman 2000b). Finally, you should take care that no exaggerations are made, the scientific procedures are not oversimplified, and the characters of the story are not sanctified, but presented as closely as possible to the reality (Allchin 2003). If any fictional elements are to be added to the story, this should be done with caution so that no historical or scientific information is distorted.

Another points for consideration when preparing a story are the learning goals of the intervention and the themes of the discussion that should follow the storytelling. During storytelling, students are actively constructing meaning as listeners, but they are passive in the sense that each student is constructing knowledge independently and connecting information to what they already know and assume. In order for the teacher to be able to actively detect valid and invalid generalizations, a discussion with the students is essential after the story is told. Keeping in mind the learning goals and the themes to be discussed with students when organizing your story can turn to be really helpful, as it helps to keep the focus to parts of the story that can illuminate the concepts to be taught.

27.2.2 *The Storytelling*

When telling a story, a storyteller does not reproduce a script; he/she has not memorized any text; it is not words he/she has in mind while telling; it is *images*. A story is composed of images that follow one another like in a movie. While telling a story, the storyteller *sees* those images in his/her mind, and all he/she does is describing them. The storyteller *tells the images* he/she sees and lets the listeners create their own *personal mental images* that constitute the story in their own minds.

27.2.2.1 Designing Your Personal Version of the Story

Read your "script" carefully; identify the episodes of the story and take some time to realize all that happens during each episode; that is important for the flow of the story and for the episodes to follow. Single out the points of the story with scientific or historical content, and make sure you are clear about them.

Try to minimize superfluous information. Perhaps you should not tell all the names of the characters of the story or not even all the episodes as students may get confused; keep only the necessary and consider if any simplifications may be essential.

After this point, try to put the "script" aside and attempt to tell the story as "gossip," something that happened yesterday and you saw with your own eyes. Be direct and fast. That way you can find the main incidents of the story, make it more proximate, and will allow yourself to disengage from the script.

Deconstructing the story is an important next step so that you get the "skeleton" of the story and its inner meaning for you. There are many ways to do so. For example, you can sketch seven successive pictures that present the story, and then write one word for each picture. Go on writing down three words for the whole story and end writing down just one word for the whole story. Alternatively, you can create the *Narrative Pyramid* of the story (Ellery and Rosenboom 2011) and/or write a haiku (3 verses with 5–7 – 5 syllables, respectively) that summarizes the story. Figure 27.1 presents examples of such deconstructions based on the story of *The Double Helix* that we have provided as an Appendix to this chapter.

After having deconstructed the story, you can build it up again with your personal images, feelings, words, and meanings. To enrich those images as much as possible, you have to imagine them in a thorough detail, as if preparing the scenery for a movie (e.g., what color are the walls in Franklin's lab? What are the benches made of? What is she wearing? How is the floor, her shoes etc.?). Although these details will never be told, they are important to strengthen the storyteller's images and the story's atmosphere and to make storytelling more convincing.

Furthermore, for the story to be vivid, it should contain visual images as well as feelings of all the senses, like smells (e.g., the smell of mold in Watson's room or the chemicals in Franklin's lab), tastes (e.g., the beer they drank), sounds (e.g.,

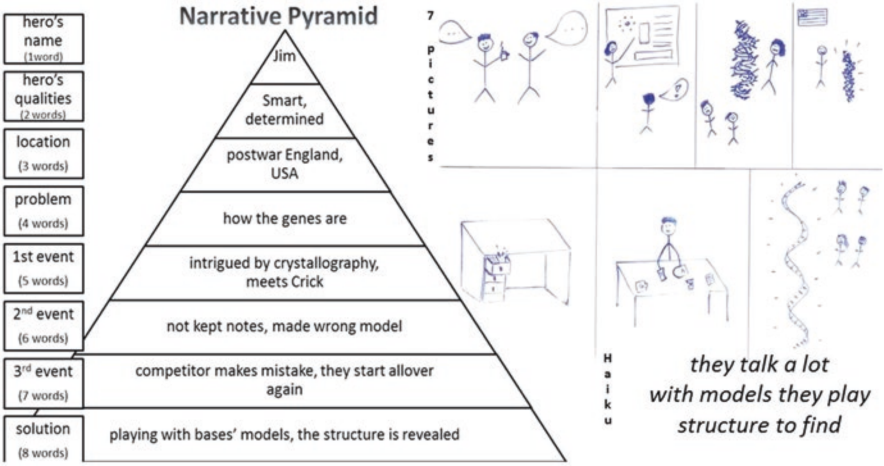

Fig. 27.1 "Deconstructing" exercises for the story of *The Double Helix: Narrative Pyramid*, Seven Pictures, Haiku

Crick banging the door open), and touch feelings (e.g., the cold, smooth, metallic pieces they used to build their model, etc.).

As to the length of the story, you must keep in mind that you don't want your story to be very long in order to have enough time for a conversation with your students in the end of the storytelling or for another activity. The length of the story can be adjusted by picking which parts of the story, which episodes, should be told in detail and which not. The selection depends on the parts of the story which are necessary for the plot, as well as on the aspects of the story you want to illuminate. The rest can be briefly told, like a reportage giving only the necessary information for the plot to go on, and then when you reach a significant part again, you can zoom in and tell all about it in detail. Alternatively, you may choose to tell just a part of a story that contains the information you wish to introduce to your students, and that can be enough to initiate an interesting dialogue about some NOS aspects, for instance, how Watson and Crick gained access to the DNA data from Franklin.

27.2.2.2 Telling the Story

As the story is to be told orally to the students (or read aloud to them), you should keep the speech as simple and direct as possible. Listeners have to immediately understand what you mean in order to follow the story, as there is no chance to look back as might be the case in the written account. Therefore, repetitions of important information, especially in the beginning of the story, are necessary, as well as using exactly the same words whenever referring to a person, an object or an idea.

The sentences should be short, even just four words, and simple; subordinate clauses should be avoided. For example, you may say: "James Watson who was then

23 years old and already held a PhD arrived in Cambridge in 1950." Or you can break it into smaller sentences and say instead: "In 1950 James Watson arrived in Cambridge. He was 23 years old. And he already held a PhD." That way the speech gets more direct.

Too many descriptions and information should also be avoided, the facts shall be revealed by the *actions*. Moreover, since it is oral speech, it will probably be followed by nonverbal forms of communication such as looks, nods, and gestures that achieve communication in a deeper level than mere speech does (Ong 1997).

Of course, if you do not feel comfortable with telling the story by heart, you can read it vividly to your students. If you are well familiar with the story, and if you have kept the script simple, it can be just as personal, and you may catch your eyes looking into your students' eyes instead of the lines many times, achieving successful communication just as well.

We mentioned before that facts shall be revealed by the *actions*. There are four elements in a storytelling: *action*, *description*, *feeling*, and *comment*. *Action* is what moves us forward into a story, it is about what happened, and it is described by verbs (e.g., he knocked the door, entered the room, approached the desk, and looked into his professor's eyes). Note though that not all verbs describe actions; if I just say "he decided to talk with his professor," it is not clear if he actually did so. He may have changed his mind or encountered an obstacle. Clarity is essential. The greatest part of storytelling should consist of *actions*. Describing an experiment or a research with sequential *actions* could be very helpful for understanding the *method* the particular scientist followed to reach his/her conclusions [e.g., He arrived at the Broad Street Pump. He moved the handle of the pump up and down until water ran. He filled a small bottle with water and left. He took it to a friend, who was a chemist. The chemist looked through the glass of the bottle. He saw some white floating pieces and said: "Nothing worrying here, it is similar to the water of other pumps" (*The Suspect Pump*; see Table 27.2)].

Description is achieved through adjectives, adds atmosphere to the story (e.g., the dark, cold room), or clearly illustrates something (e.g., the shiny, cold, metallic plackets). It might be very helpful to give certain scientific information implicitly; it should be sparingly used though; otherwise, the story would tire the listeners.

Feelings should be communicated through images and *actions*. The words "anxiety" or "agony" do not give such a direct message as the image of a man getting pale and having drops of cold sweat on the top of his forehead. *Feelings* are important to be described so that students can identify with the heroes and discover the human side of science.

Finally, *comments* come naturally to express the storytellers' views about the story. When they are not absolutely necessary, they should be avoided, as each listener should be free to form personal views. Yet *comments* are very helpful in science stories, when scientific or historical information should be given or when a philosophical or sociological question is addressed to the students. You could lower your voice and in a conspiratorial style make the comment, breaking the flow of the story and getting closer to your students (e.g., "You know how women did not get

Table 27.2 Stories derived from the history of biology that can be told in class to approach NOS aspects

Story/(indicative references)/heroes	Plot	Indicative NOS-related conversation topics
The Double Helix/ (Watson 2012; Crick 1998)/James Watson (JW) Francis Crick (FC) Rosalind Franklin (RF) Maurice Wilkins (MW) Linus Pauling (LP)	JW wishing to uncover the mystery of life reached Cambridge where he met FC to discover that they share same wishes and thoughts. They decided to work on the DNA structure but were not able to take crystallography X-rays of DNA as this was the subject of RF and MW team in London. JW attended a speech of RF but did not keep notes. Based on his memory, JW and FC built a triple helix model of DNA which they showed to MW and RF who dismissed it. JW and FC were requested to stop investigating DNA structure, but when the American professor LP made the same "mistake" as they had done and published it, they started building models again. JW saw an X-ray taken by RF and got convinced about the helix structure; FC found access to RF's data, and based on that, they built the double helix model which was now accepted by MW and RF. They all published their complementary results in April 1953 in successive papers in Nature	Method followed by JW and FC Women's position in science Scientists' collaboration and competition
Typhoid Mary/ (Brooks 1996; Soper 1939)/Mary Mallon (MM) George Soper (GS)	The health inspector GS was called to investigate the case of a typhoid fever outbreak in a summer house. He examined samples from the well, the sewage, the garden soil, the close by market, etc. but found nothing. After questioning the members of the family and the staff of the house, he found that the cook had left in fear of getting ill. He investigated about her, finding that typhoid fever outbreaks had occurred in seven houses she had worked before. He searched for her. He found her working in a house where two people were down with typhoid fever. He asked her if she had ailed in the past and asked for blood, urinal, and fecal samples for examination. MM was offended and refused any cooperation. GS with the help of health authorities and police had her taken to a hospital, where *Salmonella typhi* was identified in her fecal samples. She refused surgical treatment or any cooperation with the doctors. For a year, she was quarantined in a small island in New York until she signed she would change profession and then got released. A few years later, GS had a phone call from the manager of a maternity hospital where a typhoid fever outbreak was on. MM had changed her name and was working there as a cook. She was arrested and led to the quarantine island where she lived until the end of her life	Method followed by GS The reasons why MM would not cooperate with the American authorities

(continued)

Table 27.2 (continued)

Story/(indicative references)/heroes	Plot	Indicative NOS-related conversation topics
The Silenced Robins/(Morgan 2012; Wallace and Bernard 1963; Carson 1962; Wallace 1958)/George Wallace (GW) John Mehner (JM) Richard Bernard (RB) Rachel Carson (RC)	GW was an ornithologist, professor in MSU. In 1954, one of his doctoral students, JM, started studying the population of robins in the MSU campus and the suburbs. In the Spring of 1955, robins started dying; in a few days, the whole state was full of dead birds. GW and JM soon connected the death of the birds with the extended use of DDT, but could not yet explain how the birds were intoxicated by the insecticide. The year JM completed his thesis, he had found only one robin in the whole campus. One day a student reported to GW a strange incident. In the wildlife laboratory, all the crawfish died and a snake got intoxicated after being fed with worms from the campus. GW got it; it was the worms that intoxicated the robins. Soon later a paper from another researcher was published, confirming GW's hypothesis. DDT was found in leaves' samples, worms' tissues, and dead robins' tissues. In 1958, GW published his observations and his conclusions in a paper named "Insecticides and Birds," attributing the reduction of the robins' population to the use of DDT. It got well known very soon, and the reaction was huge; farmers, professors, and the company that produced DDT accused him of practicing nonscientific methods and pressed the MSU to discharge him. Only after the intervention of a congress member who believed in GW did he save his job. RC contacted him at that time, encouraging him to go on. Another doctoral student of his, RB, started analyzing tissues of the dead robins; his thesis proved that DDT was concentrated in the brain, the liver, the fat, the ovaries, and the testicles of the robins neutering and killing them. In 1962, RB's thesis was published, and no one could question GW's view anymore	The importance of scientists' communication The way economics and politics affect science How the publication of RC's book reinforced the environmental movement

(continued)

Table 27.2 (continued)

Story/(indicative references)/heroes	Plot	Indicative NOS-related conversation topics
Darwin–Wallace: Individual Minds, Common Thought/(Beccaloni 2008; Leff 2008)/ Charles Darwin (CD) Alfred Russel Wallace (ARW)	CD was a 22-year-old aristocrat who loved collecting beetles when he was offered a position on the Beagle, the corvette that was to map South America coasts and travel around the globe. Dreaming of adventures in exotic spaces and opposing to his father's will, he accepted, under the condition to cover his own expenses and to be able to leave the ship whenever he willed. He spent the sailing days being sick and studying and the rest being astonished, exploring and selecting specimens of stones, plants, and animals. He observed and wondered how could it be that there were so many different organisms in small islands like the Galapagos and how could it be that there were similar organisms in very distant places. In five years, he returned, and he published his travelling diaries, got married, and started studying the specimens he had brought back. He soon came up with the ideas of a common ancestor of all living organisms, natural selection, and evolution. But he hesitated to publish and waited until he had studied all his specimens. ARW loved collecting beetles and he dreamed of travelling to exotic spaces; he was 25 when he sailed to Amazon, intending to select specimens to sell to zoos and aristocrats to make some money. He explored and selected specimens of plants and animals. He observed and wondered how could it be that there were so many different organisms in the world? In the return trip, the ship and all his endeavors got fire. A few years later though, he sailed again; this time he sailed to the Malay Archipelago, where he lived with the locals, observed, and gathered specimens, wondering about the diversity of life. He had a fever when the mechanism of evolution came to him. He wrote down his ideas and sent the letter to CD whom he respected. When CD received the letter, he was shocked to read his own ideas written in different words by ARW. Encouraged by scientists-friends, he wrote a summary of his own ideas as well and sent the two scripts to be presented at the next Linnean Society meeting. That was the first announcement of the theory of evolution signed by both men who kept an honest friendly relationship ever after	Similarities and differences between the two heroes The reason why CD hesitated to publish his theory The relationship between the two heroes

(continued)

Table 27.2 (continued)

Story/(indicative references)/heroes	Plot	Indicative NOS-related conversation topics
The Suspect Pump/(Brody et al. 2000; Snow 1855)/ John Snow (JS)	On the last day of August 1854, JS was informed that there was a cholera outbreak in a region in London. Four people lost their lives on that day and on the next day 79. Most of the deaths occurred nearby the Broad Street where there was one of the biggest water pumps in London. JS, who had previously studied cholera's epidemiology, considered it was spread by water, and not by "bad air," or else "miasma" like other doctors believed. He went there, took a sample of the water, but found nothing worrying. People kept on dying. He asked for a list of the cholera deaths. Most of the dead lived close by the Broad Street. He visited the houses of the ones who lived further, discovering they all used to drink water from the Broad Street pump. He drew a map of the area and marked on it the 500 deaths that had occurred until then, and he took it to the local authorities persuading them to remove the handle of the pump. The cholera outbreaks stopped. JS wrote a book on his hypothesis and study which was not accepted by the scientists of his time. Only after the Germ Theory was established by Koch's and Pasteur's work was his theory accepted	JS's method The circumstances that fostered the cholera outbreak in London in 1854 The reason why John Snow's theory was not accepted by his contemporary scientists
A Radical Symbiosis/(Goldscheider 2009; Margulis 1995)/Lynn Margulis (LM)	In 1963, LM a 24-year-old PhD student, bright, determined, and divorced mother of two boys, was intrigued by puzzling patterns of heredity and by a picture showing that DNA resided in chloroplasts. In 1966, she wrote a theoretical paper titled "On the Origin of Mitosing Cells," which was rejected 15 times, as well as her requests for funding. In 1967, the paper finally got accepted by the "Journal of Theoretical Biology," and although it was soon awarded, her colleagues understood little of it and often mocked her. She remarried and had two more children. She was teaching in Boston University when a paper which experimentally proved her endosymbiotic theory was published in 1978. She got a second divorce but stood always loyal to science and her children who were half raised in the lab. Her book "Origin of Eukaryotic Cells" (1970) is considered as contributing to a paradigm shift in evolutionary biology	The reasons LM's original paper was turned down What it takes for a paradigm shift in science

(continued)

Table 27.2 (continued)

Story/(indicative references)/heroes	Plot	Indicative NOS-related conversation topics
Solving beriberi/(Klassen 2014; Frankenburg 2009)/Christiaan Eijkman (CE) Cornelis Winkler (CW) Dr. Pekelharing (Dr P) Gerrit Grijns (GG)	On the 23rd of November 1886, a medical team arrived in Jakarta with the mission to isolate the cause of beriberi and find a cure. They set up a laboratory and started searching for a responsible bacterium. Within 8 months, they isolated a bacterium, but Dr. Koch's postulates for establishing the bacterial cause of beriberi were not met. During the team's last meeting before sailing back to The Netherlands, CW recalled how local people attributed beriberi to insufficient nourishment, but Dr. P did not take him seriously. CE stayed back to continue investigating. One day he was informed about chickens being sick with beriberi; so he now had an animal model at his disposal. He ran experiments, dividing healthy from unhealthy chickens and trying to infect a group of healthy ones with the suspected bacterium, but all the chicken would turn sick and to his confusion one day they suddenly all turned well. He soon found out about a difference in their diet since they got well and started such experiments, concluding that feeding white or polished rice resulted in the chickens acquiring beriberi, while feeding them rice containing the bran cured the disease, but he could not explain the actual mechanism. In 1896, he had to go back to Amsterdam. It was his successor in Jakarta, GG, who in 1901 established that beriberi was caused by a deficiency that appears in absence of a natural food substance	The reasons why the research team was looking for a bacterium CE's method
The Mystery of Breathing/(Kokkotas 2014)/Antoine Laurent de Lavoisier (ALL) Marie – Anne de Lavoisier (MAL) Armand Seguin (AS)	During a party, AS expressed his admiration for MAL's help to her husband's research. MAL mentioned her questions about his last experiment and the two men volunteered to show it to her. AS puts on a full-face mask which was connected to a flask filled with alkali liquid. He sat still and breathed into the mask; all the exhaled air was collected into the flask. The carbon dioxide reacted with the alkali liquid, and an indissoluble alkali carbonate was generated. MAL could see the bubbles of the air going up into the flask and after a short while dust gathering to the bottom of the flask. ALL timed the experiment. Then he disconnected the flask and connected another one, also filled with alkali liquid, to the mask. He then asked AS to jog for the same amount of time. More alkali carbonate was gathered at the bottom of the flask. ALL explained his inferences about how oxygen is related to respiration and to the heat production in animals' bodies	ALL's method The way ALL's findings changed what was considered to be the "scientific truth" until then

paid the same as men at the time, and it was very rare for one to be a scientist. Wilkins considered Franklin as his assistant and not as an equal researcher" and then go on with the story).

27.2.3 After Storytelling: The Dialogue

Once you have finished telling the story, a *dialogue* with your students should follow. Encourage students' interventions either during storytelling or afterward so that you can pick a subject and lead the conversation to NOS-related issue. Through the discussion, all the *Whys* shall be answered referring to NOS.

Since storytelling cultivates trust between students and teachers and encourages communication, students get motivated to express their opinions more easily and are open to discussion after having heard a story from their teacher. Moreover, when a story is derived from the HOS, many NOS aspects are included in its content, and discussing the story can lead to discussing about NOS, always under the careful guidance of the teacher.

The dialogue can begin with a simple question by the teacher like "What did impress you the most in the story you heard?" Answering the question, the students will have the opportunity to express themselves and express their attitudes toward the story and toward science in general. Then, the teacher will lead the conversation to aspects of NOS he/she has chosen to teach.

At this point, it may be useful to explicitly explain the certain NOS aspects. With the students' help, you may find arguments based on evidence from the story that has just been told. For example, if you have told *The Suspect Pump* (see Table 27.2) and you wish to teach about the tentative nature of scientific knowledge, you can first explain how the scientific knowledge may change under the light of new scientific evidence and ask your students if they recognize such a pattern in the story.

Alternative ideas may be revealed through the conversation, and you have the chance to discuss them. You can even ask your students to evaluate some common alternative ideas as true or false based on the story they have heard. For example, you can claim that "Some people tend to believe that scientific ideas are absolute and cannot change, how do you evaluate this claim, based on the story you've heard?"

Such an approach puts the students in the condition of reflecting on the story they have heard to drive conclusions about NOS aspects. Such an explicit reflective approach has been found to enforce better NOS understanding (Abd-El-Khalick and Lederman 2000a).

27.3 Examples and Suggestions for Effective Teaching of NOS-Related Issues Through Storytelling

Telling stories can be amusing and satisfying for both teacher and students, and it can result in a better class climate. Telling stories derived from the HOS achieves more pedagogical and epistemological benefits, including better NOS understanding. Each HOS story conveys many NOS issues that can be revealed through a fruitful conversation.

The following table lists some examples of HOS stories (Table 27.2). Of course, the list of the table is not complete; it simply contains stories we have worked on, which match with the Greek curriculum. More examples can be found in web sources as the ones presented in Table 27.1. At the first column of Table 27.2, you can find the title of each story, a few indicative references for it, and the names of the heroes of the story. At the second column, there is a brief summary of the plot of each story. In the third column, there are some indicative NOS-related topics for each story which can lead to fruitful conversations about NOS aspects; more of such topics may be derived from each story.

As mentioned, telling such HOS stories can be really helpful for teaching NOS, but mere storytelling is not enough. The teacher must be prepared about the aspects of NOS he/she wishes to teach, to organize the storytelling in a way that will highlight the respective points of the story, and to prepare the corresponding topics for discussion.

27.3.1 Relating HOS Stories to Various Aspects of NOS

Below follows a discussion on the McComas list of NOS aspects (see Chap. 3) as approached through storytelling.

27.3.1.1 Science Depends on *Empirical Evidence*

Most of the historically based science stories follow their hero, a scientist forming hypotheses that are not enough to convince the scientific community about his/her ideas, so he/she is agonizing to gather enough scientific evidence to support his/her hypotheses (e.g., *The Silenced Robins*, *A Radical Symbiosis*; see Table 27.2). Sometimes though the hero's initial hypothesis is overturned by empirical evidence (e.g., *Solving Beriberi*; see Table 27.2).

Through storytelling, a scientist's thoughts, hypotheses, efforts, disappointments, and triumphs are followed closely, so an induction can be made about what it takes for scientific knowledge to be produced, and how important empirical evidence is in order to draw safe conclusions.

27.3.1.2 Science Shares Many Common Features in Terms of *Method*

Storytelling can enlighten the nature of scientific method and conduce to overcoming the misconception of the existence of one specific scientific method followed by all scientists that always leads to scientific knowledge (Woodcock 2014). When following a science story, one can follow all the steps that led to a discovery; especially when the scientist's actions are clearly described in detail, as proposed above, it becomes easy to understand exactly how each scientist discovered what. That way, students can compare the procedure followed in the story with what they already know about scientific methods. Moreover, listening to different stories, they can come to acknowledge that there is no such thing as *the* scientific method followed by all scientists; rather there is a wide spectrum of methods that can lead to scientific knowledge, which can be as wide as human creativity is. For example, *The Double Helix* (see Table 27.2) is an example of why experiments are not the only route to knowledge but also an example of a revolutionary discovery. *The Mystery of Breathing* (see Table 27.2) is an example of experimental science. *The Silenced Robins* is a more "traditional" example of a multistep scientific endeavor. Whereas *Darwin–Wallace* (see Table 27.2) constitutes the conception of a scientific idea and the establishment of a theory based on mere observation.

After having listened to a scientific story, students are in a position of discussing the described scientific method and contrasting it to what they have known until then. If they get to listen to more than one story during a science course, they will also get more examples of different paths that lead to knowledge and will have a more complete picture.

27.3.1.3 Science Is *Tentative*, Durable, and Self-Correcting

Most science stories describe a change in what was considered as scientifically correct in the era of the story. In the beginning of the story, the "scientific truth" of the time is usually explained, which probably will be later shifted by the scientist's discovery. For example, regarding *The Double Helix* (see Table 27.2), most scientists of the time were not yet convinced about the significance of DNA, something that was overturned after the double helix discovery. In *The Silenced Robins* (see Table 27.2), DDT was considered to be completely safe for higher organisms, yet robins died. In John Snow's time, it was believed that diseases got spread by a miasma (*The Suspect Pump*; see Table 27.2).

Storytelling gives teacher and students the opportunity to travel back in time and take a close look to how scientists used to think back then, fully understand what was considered as scientifically correct and why, and while they follow the scientist's endeavors through the unfolding of the story they understand what it takes for a shift to be achieved. That way, the tentative, yet durable, character of science is revealed.

27.3.1.4 *Laws and Theories* Are Not the Same

In biology, almost all generalizations have a probabilistic nature; all biological laws have exceptions (Mayr 2008). As far as theories are concerned, the HOS stories can enlighten what it takes for a theory to be established as a broad conceptual framework that can explain a phenomenon. For example, *Darwin–Wallace* (see Table 27.2) contains elements about the theory of evolution by natural selection. *The Suspect Pump* (see Table 27.2) refers to a different disease transmission theory from the one that is accepted today, which affected a lot the way Snow's findings were dismissed or accepted by the contemporary scientific community.

However, for students to understand what a *theory* is and how it is different from a *law* or a *hypothesis*, storytelling is not enough, but it can give rise to fruitful conversations under the right guidance. For instance, the lead could be questions such as why was John Snow's hypothesis for the transmission of cholera rejected, when he was proven correct, what else was known until then, and how the germ theory of disease was established.

27.3.1.5 Science Has *Creative Elements*

Unfolding a science story and following closely the scientist's/hero's thoughts and actions that led him/her to a discovery equals to reviving moments of frustration, agony, inspiration, and even "Eureka" that led to the discovery.

All science stories describe creative processes, e.g., making a DNA model with paperclip wire, map drawing of the Amazon rainforest, etc. They also have a special moment when inspiration illuminates the scientist's mind, e.g., when Watson cut out of paper the shapes of the nitrogenous bases of DNA and started combining them to see how they pair, or when A. R. Wallace had a vision of natural selection's mechanism, while he was down with a high fever, or when G. Wallace learnt about the shrimps that died and the snake that went down with spasms after having eaten worms, etc. (see Table 27.2).

Through storytelling, teller and listeners are able to live those moments and to understand the critical mind, the intelligence, the observation, the insight, the creativity, the inspiration, and the good timing it takes for a discovery to be achieved through a process that turns out to be exciting.

27.3.1.6 Science Has a *Subjective Component*

As a human activity, science has a subjective component: it is possible two scientists examining the same data to draw different conclusions influenced by their prior experiences and expectations. There are stories from the HOS that present such examples, and storytelling could be a good way to make students familiar with the different ways of thinking as they affiliate with different heroes of the story. Through storytelling, one may understand the intentions and the influences of a scientist, as well as how these affect his/her work.

In the *Double Helix* (see Table 27.2), for instance, almost all of the data that Watson and Crick laid on to build their model were owned by Franklin; actually, it was her experiments that resulted in that data. Yet, in the beginning, she interpreted them differently and believed that further crystallography research would be needed before any safe conclusion could be drawn. She was actually preparing to leave her work on DNA for another academic position. Watson and Crick on the other hand, who dreamed to uncover the secret of life, were obsessed with the DNA structure. Crick had been working on a similar protein structure for his thesis, so his previous experience allowed him to acknowledge at once the significance of Franklin's data and analyze them faster (Cobb 2015).

27.3.1.7 There Are *Historical, Cultural, Political, and Social Influences* on Science

Scientists as humans are social beings that are inevitably affected and influenced by the society in which they live. Their work and their endeavors may get affected either by widespread ideas and the scientific paradigms of their time that can prevent scientists from accepting an alternative scheme or by the fact that their research may not get funded because it does not attract the interest of investors, as a result. The HOS stories as they describe the facts from a historical perspective reveal the historical, cultural, political, and social influences on scientists and by extension on science. Storytelling may be an excellent way to approach such influences, as it is a way of closely observing the scientists' moves and of understanding their motives, the factors that affected them, and the broader situation of their time. Students after listening to a story can make connections and comprehend how science is influenced by historical, cultural, political, and social factors.

For example, in *The Silenced Robins* political and social influences are obvious as the scientist George Wallace almost lost his job due to the fact that the results of his research negatively affected the interests of a company which was an important economic power of the time. Had this happened, his research might have stopped. It took the intervention of a politician for him to keep his job and for the research to be completed. In *Darwin–Wallace*, cultural influences are obvious as we see that Darwin hesitated to publish his work for 20 years because of the religious climate of the time. Whereas in *The Double Helix*, social influences are evident in several points; for instance, unwritten ethical rules prevented Watson and Crick from investigating the same subject with Wilkins and Franklin, and later on the competition between scientists is revealed as they strived to reach to the discovery before Pauling (see Table 27.2). The examples of such influences when examining scientific stories are endless, and they can be very useful to help students make connections with situations of today.

27.3.1.8 *Science and Technology* Impact Each Other, But They Are Not the Same

Through HOS stories, it may get clear to students that although science and technology are interconnected, they are not identical. After the narration of the story, during the conversation, the attribution of science to technology and vice versa can be discussed based on the given examples of the story. For example, in *The Double Helix*, the structure of the DNA could not have been possibly revealed without the technology of X-ray and crystallography. On the other hand, in *The Suspect Pump*, there is an example of how the technology is not always enough for a discovery to be made. At the time, microscopy had been invented. In fact, Snow examined a water sample from the Broad Street pump under the microscope, and although there was organic matter in it, as well as oval-shaped life forms, he could not attribute the spread of the disease to them (Johnson 2006) as the germ theory of disease was not established until Pasteur's work (1859) (see Table 27.2).

27.3.1.9 Science *Cannot Answer All Questions*

Science has limits. Not everything can be explained by science, at least not yet. Still, there are domains that will always be outside the realm of science such as moral judgements, aesthetic judgements, decisions about applications of science, and conclusions about the supernatural ("Science has limits: A few things that science does not do" 2018).

It is very possible that through the stories, philosophical questions may arise, ones that science cannot answer, especially when the stories concern subjects such as the Big Bang or the beginning of life, e.g., the primordial soup. Teachers should be prepared for such questions, especially from teenagers, and make it clear to them that science does have limits; it can only give explanations about the natural world, and it can't solve every existing problem.

27.4 Assessing the Effectiveness of Storytelling in Teaching NOS-Related Issues

In order to assess the effectiveness of storytelling in achieving the abovementioned goals, we have organized an experiential storytelling workshop for biology teachers, during which, four of the stories of Table 27.2 were handed to them. Each of the stories was accompanied by some discussion topics that referred to NOS aspects. Teachers then used the storytelling method, in their classes, and gave us feedback. Methodological triangulation (structured, close-ended questionnaire, semi-structured interviews, and natural, nonparticipant, structured observation) was used in order to collect data about the effectiveness of the method.

Table 27.3 Teachers' opinions about whether a story (from Table 27.2) fits a NOS aspect

	Story			
NOS aspect	Double Helix	Typhoid Mary	Silenced Robins	Darwin – Wallace
Reliance of empirical evidence	18.2%	59.1%	50%	45.5%
Thoughts about the nature of the scientific method	72.7%	45.5%	63.6%	50%
Scientific knowledge is tentative, durable, and self-correcting	22.7%	13.6%	18.2%	36.4%
Definition and distinction of laws and theories	04.5%	–	04.5%	13.6%
Creative elements in science	50%	22.7%	31.8%	45.5%
Scientists may be subjective (theory-laden)	27.3%	18.2%	40.9%	27.3%
There are historical, cultural, social, political influences on science	50%	40.9%	45.5%	63.6%
Distinction and relationships of science and technology	18.2%	04.5%	–	04.5%
Limitations of science	09.1%	13.6%	13.6%	27.3%

Teachers' evaluation of storytelling regarding its reference to NOS aspects is presented in Table 27.3. Almost all NOS aspects were identified in all stories by a rather small or great percentage of teachers. The mostly mentioned NOS aspects were those regarding the nature of scientific method and social influences of science, followed by the ones about the need for empirical evidence and creative element of science. Each story was found to mostly correspond to a NOS aspect: *Double Helix, Silenced Robins*, nature of scientific method; *Darwin–Wallace*, historical, cultural, and social influences; and *Typhoid Mary*, the need of empirical evidence. The least mentioned aspects were those about laws and theory and about science and technology.

We attribute these results both to the content of the stories and to the familiarity of the teachers with some aspects of NOS; for instance, understanding the nature of scientific method is a clear objective of the Greek curriculum.

The results of teachers' interviews in detail will be presented in a future paper, but indicatively we should mention that all of the interviewed teachers were impressed by the success of the storytelling in catching their students' attention, and they reported a feeling of satisfaction by the end of the lesson. Most of them claimed that after the storytelling, a conversation about NOS aspects took place. Interestingly most teachers claimed that if it were not for the story, there would not be any NOS conversation.

27.5 Conclusions

Learning something about NOS is an important goal of science learning and as such must be an important part of science instruction. Yet, mainly due to lack of time, resources, curriculum models, and even personal understanding, teachers frequently neglect it (Höttecke and Silva 2011). History of science is alive with potential examples for demonstrating important NOS elements. We suggest that such examples should be introduced in the class through storytelling, which assures successful communication and strengthens the relationship between teacher and students. Telling stories derived from the HOS in combination with class conversation may be a sufficient method to teach NOS, in an easy and satisfying way for the teachers to apply.

Research conducted to test the above suggestion has shown that teachers recognize the importance of storytelling in applying NOS aspects and that they are willing to implement it. Moreover, the method is also effective for teaching science content along with NOS aspects (Mavrikaki and Kapsala 2012) and results in increased students' attention and participation (Kapsala et al. 2015).

Storytelling has the potential to incorporate the scientific historical cases to the contemporary oral tradition. Thus, teachers can be given the ancient and sacred role of the storyteller, who will introduce the students to all the wonderful stories of science and our civilization (Egan 1986).

Acknowledgments We gratefully acknowledge the contribution of all the biology teachers who attended the storytelling workshop and gave us feedback. This work was supported in part by NKUA (66469/2016).

Appendix: Brief Example of a Story: *The Double Helix*

In 1950 in the laboratory of Cavendish in Cambridge two men met. James Watson was 23 years old and he already owned a PhD. Francis Crick was 35 and a PhD student. They immediately got along. They shared the same thirst to discover the secret of life and agreed that DNA had to do with it, although most scientists of their time were not yet convinced about DNA's importance.

They both knew about the discovery of a legendary chemist from America: Linus Pauling. He had discovered the alpha helix structure of the polypeptide chain. It was the first time anyone had shown for sure what the shape of such a small molecule was. Pauling had reached his result based on X-ray crystallography and molecular model building, using models that resembled children's toys. James and Francis very soon decided to do the same with DNA.

James knew nothing about X-ray crystallography; Francis was an expert. There was an obstacle though. Another group in London worked on DNA X-ray crystallography. Thankfully Francis knew the leader of the group, Maurice Wilkins. He invited him for the weekend. Over dinner Francis enthusiastically informed him about their intentions. Maurice did not agree with the model-building. He shared some information indicating a helix structure, but he couldn't tell much. Another researcher was currently working on the project; Rosalind Franklin. Maurice barely talked to her and didn't know about her progress. But in a few weeks she would give a seminar about her results. Maurice turned to James, "If you wish, you are welcome to attend it". Of course he wished.

The day of the seminar arrived. James was sitting at the back of a cold university room. He tried to bring in mind all the details Francis insisted he should pay attention to. Rosalind entered the room. She spoke fast, avoiding to look straight at her audience. James gazed at her. "If she changed her hair, and put on some lipstick, one would call her pretty!" Soon he concentrated to her words. She considered her findings very preliminary, "more facts should be gathered before one could speculate about DNA structure".

But her results seemed important to James. As soon as he returned to Cambridge he reported to Francis all he could recall, and Francis combined the scrappy data with theories about helix structures. Soon they started building models. In three days they had come up with the structure! It was a three stranded helix. Each of the strands spiraled around the other two. Their sugar-phosphate backbones were in the middle and the nitrogenous bases at the outside of the molecule.

They immediately called the London team. The next morning, they arrived in Cavendish. They entered the lab. Francis loudly explained his helix-theory. Rosalind started tapping her shoe on the floor. "There is no proof that DNA has a helix structure" she claimed, and turned to examine the model. "It is wrong!" she said, "DNA has at least ten times more water than what you represent." James had transferred the data wrong.

Their professor ordered them to stop working with DNA models. So they did for a whole year.

One day an envelope from America arrived at the lab. It was from Linus Pauling. Francis tore the envelope open. Inside there was a letter and a scientific paper. He read the letter aloud. It was the worst news. Pauling had discovered the structure of DNA. James with bated breath grabbed the paper and started reading. It was proposing a three stranded helix with each of the strands spiraling around the other two, their sugar-phosphate backbones in the middle and the nitrogenous bases at the outside of the molecule. "That's what we said", James mumbled. Francis took the paper and read for himself. Then James took it back. Something was wrong. They both agreed. They went to the biochemists of the building and asked them. Pauling was wrong! They strolled to Eagle, the bar, and drank to the failure of Pauling.

Next day James took the train to London, to break the news to the London team. Rosalind was not interested, and neither was Maurice, but at some point Maurice showed James a DNA X-ray image. It was a new type Rosalind had recently taken. When James saw it, his mouth fell open and his heart beat faster. It was the simplest DNA X-ray image he had ever seen! It made clear that DNA had a helix structure. If only Francis could see it... He would know of how many strands it consists. In the return train, James drew at the side of his newspaper, all he remembered of the image.

They took permission to start working on DNA models again. They tried a helix with two strands. And to fit Rosalind's results, they decided to put the sugar-phosphate backbones at the outside of the molecule. James was worried; this last decision meant that the four different kinds of nitrogenous bases would have to be packed inside. How could that be? But it was late, and even he needed some rest.

He rode his bike home, entered his cold room, went to the fireplace and lit a big fire. He curled up next to the fire, hearing the crunch of the wood. As he was falling asleep, an idea awoke him. What if each nitrogenous base pairs with an identical one? He took a pencil and a biochemistry book. He copied the four bases. It was true; each one of them could bind with an identical one.

He went to the lab before dawn. He was thrilled and couldn't wait to talk about it. He told the first person who entered the laboratory. He was a crystallographer. He looked at James sketch, took a pen and corrected it. – "That cannot be", James said, "I copied the structures from the biochemistry book." – "Who says books don't make mistakes?", the crystallographer answered.

James was devastated. He went to his desk with his eyes on the corrected sketch. Now the big bases, Adenine and Guanine were much bigger, and the small ones were much smaller. If the pairing was like-for-like, there would be big bulges and niches. He did not speak to anyone that day, nor did he go for lunch.

During the evening he drew on a cardboard the four bases and cut them out. He suddenly emptied his desk and started moving the cardboard bases around trying to find how they could bind. At some point he realized that the pair of Adenine – Thymine was equal in size and shape with the pair of Guanine – Cytosine.

He called for Francis. Francis was excited! "Such exclusive pairing means that the two strands are complementary. That even explains the Chargaff's data we have read. It must be correct! And if it is correct, then... The sequence of the one defines the other's sequence. Perhaps one came by copying the other one." They went back to their model and started placing the shiny cold metallic plackets.

In one hour the model was built. It was a two stranded helix. Each strand was spiraling around the other. The sugar-phosphate backbones were antiparallel at the outside of the molecule and in the middle there were the pairs of the nitrogenous bases. This time no one had an objection.

They went to the bar to celebrate. Francis banged the door open shouting "We found the secret of life!" And so they'd had.

References

Abd-El-Khalick, F., & Lederman, N. G. (2000a). Improving science teachers' conceptions of nature of science: A critical review of the literature. *International Journal of Science Education, 22*(7), 665–701. https://doi.org/10.1080/09500690050044044.

Abd-El-Khalick, F., & Lederman, N. G. (2000b). The influence of history of science courses on students' views of nature of science. *Journal of Research in Science Teaching, 37*(10), 1057–1095. https://doi.org/10.1002/1098-2736(200012)37:10<1057::AID-TEA3>3.0.CO;2-C.

Abd-El-Khalick, F., Bell, R. L., & Lederman, N. G. (1998). The nature of science and instructional practice: Making the unnatural natural. *Science Education, 82*(4), 417–436. https://doi.org/10.1002/(SICI)1098-237X(199807)82:4<417::AID-SCE1>3.0.CO;2-E.

Abrahamson, C. E. (1998). Storytelling as a pedagogical tool in higher education. *Education, 118*(3), 440–451.

Allchin, D. (2003). Scientific myth-conceptions. *Science Education, 87*(3), 329–351. https://doi.org/10.1002/sce.10055.

Allchin, D. (2014). From science studies to scientific literacy: A view from the classroom. *Science and Education, 23*(9), 1911–1932. https://doi.org/10.1007/s11191-013-9672-8.

Beccaloni, G. (2008). *The Alfred Russel Wallace Website*. Wallacefund.info. Retrieved January 26, 2017, from http://wallacefund.info/

Boyd, B. (2009). *On the origin of stories*. Cambridge, MA: Belknap Press of Harvard University Press.

Brody, H., Rip, M. R., Vinten-Johansen, P., Paneth, N., & Rachman, S. (2000). Map-making and myth-making in Broad Street: The London cholera epidemic, 1854. *The Lancet, 356*(9223), 64–68. https://doi.org/10.1016/S0140-6736(00)02442-9.

Brooks, J. (1996). The sad and tragic life of Typhoid Mary. *Canadian Medical Association Journal, 154*(6), 915–916.

Bruner, J. S. (1985). Narrative and paradigmatic modes of thought. In E. Eisner (Ed.), *Learning and teaching the ways of knowing* (pp. 97–115). Chicago: University of Chicago Press.

Bruner, J. S. (2003). *Making stories: Law, literature, life*. Cambridge, MA: Harvard University Press.

Carson, R. (1962). *Silent spring*. Boston: Houghton Mifflin.

Cheetham, M., Hänggi, J., & Jancke, L. (2014). Identifying with fictive characters: Structural brain correlates of the personality trait "fantasy". *Social Cognitive and Affective Neuroscience, 9*(11), 1836–1844. https://doi.org/10.1093/scan/nst179.

Clair, K. L. S. (2008). Storytelling facilitates natural learning: A teaching strategy. *NEFDC EXCHANGE, 19*(2), 11.

Clough, M. P. (2011). The story behind the science: Bringing science and scientists to life in post-secondary science education. *Science and Education, 20*(7), 701–717. https://doi.org/10.1007/s11191-010-9310-7.

Cobb, M. (2015). *Sexism in science: Did Watson and Crick really steal Rosalind Franklin's data?* Retrieved December 7, 2016, from https://www.theguardian.com/science/2015/jun/23/sexism-in-science-did-watson-and-crick-really-steal-rosalind-franklins-data

Cohen, I. B. (1993). A sense of history in science. *Science and Education, 2*(3), 251–277. https://doi.org/10.1007/BF00490067.

Crick, F. (1998). *What mad pursuit : A personal view of scientific discovery*. New York: Basic Books.

Cron, L. (2012). *Wired for story*. New York: Ten Speed Press.

Cross, C. J. (2017). An analysis of storytelling on student content qcquisition. *The American Biology Teacher, 79*(8), 628–634. https://doi.org/10.1525/abt.2017.79.8.628.

Csikar, E., & Stefaniak, J. E. (2018). The utility of storytelling strategies in the biology classroom. *Contemporary Educational Technology, 9*(1), 42–60. https://digitalcommons.odu.edu/stemps_fac_pubs/56.

DeBoer, G. E. (1991). *A history of ideas in science education: Implications for practice*. New York: Teachers College Press.

Dolphin, G., Benoit, W., Burylo, J., Hurst, E., Petryshen, W., & Wiebe, S. (2018). Braiding history, inquiry, and model-based learning: A collection of open-source historical case studies for teaching both geology content and the nature of science. *Journal of Geoscience Education, 66*(3), 205–220. https://doi.org/10.1080/10899995.2018.1475821.

Egan, K. (1986). *Teaching as story telling: An alternative approach to teaching and curriculum in the elementary school*. Chicago: University of Chicago Press.

Egan, K. (1989). Memory, imagination, and learning: Connected by the story. *Phi Delta Kappan, 70*(6), 455–459.

Eichman, P. (1996). Using history to teach biology. *The American Biology Teacher, 58*(4), 200–204.

Ellery, V., & Rosenboom, J. (2011). *Sustaining strategic readers: Techniques for supporting content literacy in grades 6–12*. Newark: DE: International Reading Association.

Engestrom, Y. (1999). *Learning by expanding: An activity – theoretical approach to developmental research.* Webpublished. Retrieved from http://lchc.ucsd.edu/mca/Paper/Engestrom/Learning-by-Expanding.pdf

Frankenburg, F. R. (2009). *Vitamin discoveries and disasters : History, science, and controversies*. Santa Barbara: Praeger/ABC-CLIO.

Galili, I. (2015). On the involvement of History and Philosophy of Science in teaching Science – an approach promoting cultural content knowledge. *Review of Science, Mathematics and ICT Education, 9*(1), 7–17.

Goldscheider, E. (2009). Evolution revolution. *On Wisconsin, 61*(Fall), 44–47.

Gottschall, J. (2012). *The storytelling animal: How stories make us human*. Boston: Houghton Mifflin Harcourt.

Hadzigeorgiou, Y. (2005). Humanizing the teaching of physics through storytelling: The case of current electricity. *Physics Education, 41*(1), 42–45. https://doi.org/10.1088/0031-9120/41/1/003.

Hadzigeorgiou, Y., Prevezanou, B., Kabouropoulou, M., & Konsolas, M. (2011). Teaching about the importance of trees: A study with young children. *Environmental Education Research, 17*(4), 519–536. https://doi.org/10.1080/13504622.2010.549938.

Höttecke, D., & Silva, C. C. (2011). Why implementing history and philosophy in school science education is a challenge: An analysis of obstacles. *Science and Education, 20*(3), 293–316. https://doi.org/10.1007/s11191-010-9285-4.

Johnson, S. (2006). *The ghost map*. New York: Riverhead Books.

Kapsala, N., Mpampalekou, E., Mavrikaki, E., & Skordoulis, K. (2015). Storytelling in Biology Teaching – A case study in the range of Critical Education: The story of John Snow and the disease transmission. In D. Psyllos, A. Molohidis, & M. Kalleri (Eds.), *Proceedings of the 9th Panhellenic conference in science teaching and technology in education – Teaching and learning in natural sciences and technology: Research, innovation, and practice* (pp. 262–270). Retrieved January 26, 2017 from http://synedrioenephet-2015.web.auth.gr.

Kipling, R. (1902). The elephant's child*. Just so stories*. Retrieved January 3, 2017, from http://www.boop.org/jan/justso/elephant.htm

Klassen, S. (2006). A theoretical framework for contextual science teaching. *Interchange, 37*(1), 31–62. https://doi.org/10.1007/s10780-006-8399-8.

Klassen, S. (2014). *Christiaan Eijkman: Simplex non veri sigillum*. Retrieved January 16, 2017, from http://science-story-telling.eu/en/Array_1357

Klassen, S., & Klassen, C. F. (2014). Science teaching with historically based stories: Theoretical and practical perspectives. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 1503–1529). Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-007-7654-8_47.

Klopfer. (1969). The teaching of science and the history of science. *Journal of Research in Science Teaching, 6*(1), 87–95.

Kokkotas, P. (2014). *Antoine Laurent de lavoisier on respiration*. Retrieved January 16, 2017, from http://science-story-telling.eu/en/node/346/mid/2101

Kokkotas, P., Rizaki, A., & Malamitsa, K. (2010). Storytelling as a strategy for understanding concepts of electricity and electromagnetism. *Interchange, 41*(4), 379–405. https://doi.org/10.1007/s10780-010-9137-9.

Kolb, D. A. (2014). *Experiential learning: Experience as the source of learning and development*. FT Press.

Kouloumbi-Papapetropoulou, K. (1997). *The art of storytelling*. Athens: Patakis.

Lankshear, C., & Mclaren, P. (1993). *Critical literacy: Politics, praxis, and the postmodern*. Portland: SUNY Press.

Leff, D. (2008). About Darwin. Aboutdarwin.com. Retrieved January 26, 2017, from http://www.aboutdarwin.com/index.html

Margulis, L. (1995). Gaia is a tough bitch. In J. Brockman (Ed.), *The third culture: Beyond the scientific revolution* (pp. 129–151). New York: Simon & Schuster.

Mathews, M. R. (1992). History, philosophy, and science teaching: The present rapprochement. *Science & Education, 1*(1), 11–47. https://doi.org/10.1007/BF00430208.

Matthews, M. R. (1994). *Science teaching: The role of history and philosophy of science*. New York: Routledge.

Mavrikaki, E., & Kapsala, N. (2012). Teaching biology by storytelling. In G. Katsiampoura (Ed.), *Scientific cosmopolitanism and local cultures: Religions, ideologies, societies, proceedings of 5th International Conference of the European Society for the History of Science* (pp. 612–617). Athens: National Hellenic Research Foundation/Institute of Historical Research.

Mayr, E. (2008). *The growth of biological thought*. Athens: National Bank of Greece Cultural Foundation (MIET).

McComas, W. F. (2008). Seeking historical examples to illustrate key aspects of the nature of science. *Science and Education, 17*(2–3), 249–263. https://doi.org/10.1007/s11191-007-9081-y.

McComas, W. F. (2015). The nature of science & the next generation of biology education. *The American Biology Teacher, 77*(7), 485–491. https://doi.org/10.1525/abt.2015.77.7.2.

McComas, W. F., & Kampourakis, K. (2015). Using the history of biology, chemistry, geology, and physics to illustrate general aspects of nature of science. *Review of Science, Mathematics and ICT Education, 9*(1), 47–76.

McComas, W. F., Clough, M. R., & Almazroa, H. (1998). A review of the role and character of the nature of science in science education. In W. F. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 3–39). Dordrecht: Kluwer Academic.

Morgan, G. (2012). *The Robins of MSU, George Wallace and Rachel Carson's Silent Spring*. Retrieved January 26, 2017, from http://alumni.msu.edu/newsarticle.cfm?id=314

Nigam, S. K. (2012). The storytelling brain: Commentary on "on social attribution: Implications of recent cognitive neuroscience research for race, law, and politics". *Science and Engineering Ethics, 18*(3), 567–571. https://doi.org/10.1007/s11948-012-9378-3.

Ong, W. J. (1997). *Orality and Literacy: The Technologizing of the Word*. Heraklion: Crete University Press.

Papaliou, D. (Ed.). (1996). *Listen to a story*. Athens: Akritas.

Ratcliffe, M., & Millar, R. (2009). Teaching for understanding of Science in context: Evidence from the Pilot trials of the twenty first century Science courses. *Journal of Research in Science Teaching, 46*(8), 945–959. https://doi.org/10.1002/tea.20340.

Scheub, H. (1998). *Story*. Madison: The University of Wisconsin Press.

Science has limits: A few things that science does not do. (2018). *Undsci.berkeley.edu*. Retrieved April 24, 2018, from https://undsci.berkeley.edu/article/0_0_0/whatisscience_12

Snow, J. (1855). *On the mode of communication of cholera* (2nd ed.). London: John Churchill.

Soper, G. A. (1939). The curious career of typhoid Mary. *Bulletin of the New York Academy of Medicine, 15*(10), 698–712.

Speer, N. K., Reynolds, J. R., Swallow, K. M., & Zacks, J. M. (2009). Reading stories activates neural representations of visual and motor experiences. *Psychological Science, 20*(8), 989–999. https://doi.org/10.1111/j.1467-9280.2009.02397.x.

Stephens, G. J., Silbert, L. J., & Hasson, U. (2010). Speaker – listener neural coupling underlies successful communication. *Proceedings of the National Academy of Sciences of the USA, 107*(32), 14425–14430. https://doi.org/10.1073/pnas.1008662107.

Wallace, G. J. (1958). Insecticides and Birds. *Audubon Magazine, 61*(10), 147–151.

Wallace, G. J., & Bernard, R. F. (1963). Tests show 40 species of birds poisoned by DDT. *Audubon Magazine, 65*(4), 198–203.

Watson, J. (2012). *The double helix*. London: Hachette UK.

Wills, J. E. (1992). Lives and other stories: Neglected aspects of the teacher's art. *The History Teacher, 26*(1), 33–49. https://doi.org/10.2307/494084.

Wilson, S. M., Molnar-Szakacs, I., & Iacoboni, M. (2008). Beyond superior temporal cortex: Intersubject correlations in narrative speech comprehension. *Cerebral Cortex, 18*(1), 230–242. https://doi.org/10.1093/cercor/bhm049.

Woodcock, B. A. (2014). "The scientific method" as myth and ideal. *Science & Education, 23*(10), 2069–2093.

Zak, P. J. (2015). Why inspiring stories make us react : The neuroscience of narrative. *Cerebrum*, (February), 1–13.

Zull, J. E. (2002). *The art of changing the brain: Enriching teaching by exploring the biology of learning*. Sterling: Stylus Publishing, LLC.

Chapter 28
Using Stories Behind the Science to Improve Understanding of Nature of Science, Science Content, and Attitudes Toward Science

Michael P. Clough

28.1 Science Textbooks and NOS Instruction

Accurately portraying the nature of science (NOS) has been a long-standing goal of science education. However, achieving this end remains an elusive and vexing problem. The reasons for this are varied, but minimal standards set by governments for earning a science teaching license along with most universities' unwillingness to go beyond those minimal standards are largely to blame for poorly prepared science teachers who have little chance to effectively promote accurate NOS understanding and other desired science education goals. For instance, Backhus and Thompson (2006) reported that "at most perhaps 6% of preservice 9-12 science teachers in the U.S. will have taken [a NOS course] as a requirement." A more recent study of science teacher preparation in North America (Olson et al. 2015) noted that teacher licensure requirements varied widely, often set insufficient science content and science pedagogy requirements, and rarely included any reference to the NOS.

Having received insufficient preparation for effective science teaching, many science teachers turn to their science textbooks and other available curriculum materials to assist them in teaching. Science teachers' long-standing reliance on textbooks is well documented. For example, 40 years ago, Stake and Easley (1978) reported that:

> Over 90% of the science teachers in a sample of about 12,000 teachers said their instructional materials were the heart of their teaching curriculum 90–95% of the time. Behind nearly every teacher-learner transaction... lay an instructional product waiting to play its

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_28

> dual role as medium and message. They command teacher's and learner's attention. In a way, they virtually dictated the curriculum. The curriculum did not venture beyond the boundaries set by the instructional materials. (p. 13:66)

Textbooks continue to have a substantial impact on science instruction (Banilower et al. 2013). The science textbook selected for a particular course often defines the course scope, sequence, and depth and wrongly legitimizes teaching that content (Weiss 1993; Weiss et al. 2003). Textbooks also exert a significant influence on *how* content is taught—from the sequencing of information to the manner in which it is presented (Weiss et al. 2003).

Thomas Kuhn (1970) wrote that "[m]ore than any other single aspect of science, [the textbook] has determined our image of the nature of science and of the role of discovery and invention in its advance" (p. 143). Sadly, science textbooks are notorious for the way they wrongly portray the NOS. Over a quarter-century ago, DeBoer (1991), in his review of the history of science education, lamented that an outdated view of the philosophy of science permeates classroom practice and science curriculum materials. Postman (1995) characterizes that image as follows:

> …textbooks are concerned with presenting the facts of the case (whatever the case may be) as if there can be no disputing them, as if they are fixed and immutable. And still worse, there is usually no clue given as to who claimed these are the facts of the case, or how "it" discovered these facts (there being no he or she, or I or we). There is no sense of the frailty or ambiguity of human judgment, no hint of the possibilities of error. Knowledge is presented as a commodity to be acquired, never as a human struggle to understand, to overcome falsity, to stumble toward the truth. Textbooks, it seems to me, are enemies of education, instruments for promoting dogmatism and trivial learning. They may save the teacher some trouble, but the trouble they inflict on the minds of students is a blight and a curse. (p. 116)

More recent reviews of science textbooks (Abd-El-Khalick et al. 2017; Aydin and Tortumlu 2015; Wei et al. 2013) and popular science writing (Feng 2012) make apparent that most instructional materials continue to inaccurately portray the NOS, downplay or ignore the human effort to understand the natural world, and convey science in a manner that comes across to students as unapproachable.

However, accurately portraying the NOS in science textbooks is a complex process that faces many roadblocks (DiGiuseppe 2014). For instance, many publishers resist modifying traditional science textbooks in fear of losing market share, and many science teachers will resist NOS instruction if they see it detracting from science content instruction. Clough (2011) notes that:

> …past efforts such as *Harvard Case Histories in Experimental Science* (Conant 1957) and *History Of Science Cases* (Klopfer and Cooley 1963), despite their well-considered nature, are now out of print. Both emphasized the history of science to such an extent that many science faculty perceived the science content as secondary. (p. 703)

Höttecke and Silva (2011) analyzed obstacles to teaching the history and nature of science and grouped them as follows: (a) the culture of teaching physics, and likely science more generally, is not well-aligned with HNOS teaching and learning; (b) few science teachers possess the knowledge and skills for accurate and effective HNOS instruction; (c) curriculum and standards documents express superficial encouragement for HNOS teaching and learning, but do not provide meaningful follow-through in support of such ends; and (d) the central role science textbooks play in teaching science and their inaccurate portrayal HNOS. Reflecting these kinds of difficulties, DiGiuseppe (2014) writes that "much work still needs to be done for NOS to be represented in teaching-learning materials in the most pedagogically effective manner possible."

28.2 "The Story Behind the Science" Project

To alleviate these common obstacles and assist teachers in making accurate NOS instruction a more common part of science instruction, with United States National Science Foundation funding, a project titled *The Story Behind the Science: Bring science and scientists to life* was launched. This project (https://storybehindthescience.org) has produced 30 short (4–6 pages) historical stories that address the development and acceptance of fundamental science ideas in astronomy, biology, chemistry, geology, and physics. Table 28.1 provides the titles of all 30 stories and the NOS ideas that are overtly addressed in each respective story via inserted questions and text boxes. In addition to emphasizing the human context in science research and targeting important NOS ideas, each story also enriches the learning of science content.

Human beings are naturally drawn to and impacted by stories (Gottschall 2012), and accounts regarding how science is done provide a context that is more personable, interesting, humane, and has emotional and educative power that information alone does not. Moreover, historical and contemporary stories of science research, if used effectively, can provide compelling evidence that assists students in understanding and accepting more informed views regarding the NOS (Clough 2006). For these and other reasons, efforts to incorporate the history of science in science teaching has a long history in science education (e.g., Conant 1957; Klopfer and Cooley 1963; Matthews 1994, 2014; Hagen et al. 1996; Clough 1997, Clough and Olson 2004; Abd-El-Khalick 1999; Irwin 2000; Stinner et al. 2003; Metz et al. 2007 and many others). However, past efforts sometimes incorporated the history of science at levels that many science teachers perceived as distracting from the science content they were obliged to teach. Moreover, too often the history of science was not effectively used to draw students' attention to important NOS ideas.

Unlike several previous efforts to promote history and nature of science in science education, our project stories reflect Heilbron's (2002) admonition that:

> …wherever possible the case studies should carry epistemological or methodological lessons and dangle ties to humanistic subject matter. But never should the primary purpose of the cases be the teaching of history. (p. 330)

Because our project stories target science ideas typically taught in astronomy, biology, chemistry, geology, and physics courses, and because science teachers can infuse them when and where they deem suitable in their course, we have mitigated common concerns raised by science teachers for not using historical materials to accurately teach about the NOS.

Table 28.1 Story titles and overtly targeted nature of science ideas

Stories		Overtly targeted NOS ideas/issues
Astronomy	Detection of Black Holes: The Power of Robust Theory and Mathematics	Meaning of "theory." Importance of collaboration and imagination. No universal scientific method. Nonempirical justification of ideas
	Data Make Sense Only in Light of Theory: The Story of Cosmic Microwave Background	Role of theories. Subjectivity in science. Scientific knowledge is a product and also guides process. Private and public science
	Imagination and Invention: The Story of Dark Matter	Observation and theory. Role of theory. Theory change. Culture and subjectivity in science. Unobservable entities. No universal scientific method
	Personalities and Pride: Understanding the Origins of Elements	Underlying assumptions. Data do not tell scientists what to think. Science methods. Theoretical frameworks. Subjectivity. Methodological naturalism. Importance of coherence in data/ideas
	The Great Debate: Just How Big Is the Universe?	Acceptance/rejection of ideas takes time. Importance of creativity. Difference between science and technology. Prior knowledge impacts observation. Underlying assumptions. Data do not tell scientists what to think. That science ideas can be revised is a strength
	Accounting for Anomaly: The Discovery of Neptune	Anomalies do not demand rejection of science ideas. Science is a social endeavor. Scientific knowledge is a product and also guides process. Theory change
Biology	Charles Darwin: A Gentle Revolutionary	Science ideas often emerge over time. The wider culture impacts science thinking. Much time often passes before a science idea becomes well-established. No universal scientific method. Importance of creativity. Methodological naturalism. Science and religion are not necessarily at odds with one another
	Adversity and Perseverance: Alfred Russel Wallace	Much time is usually required for the development and acceptance of science ideas. Difference and relationships between laws and theories. Data do not tell scientists what to think. Science requires collaboration. That science ideas can be revised is a strength
	Creativity and Discovery: The Work of Gregor Mendel	Even revolutionary science ideas are tied to prior ways of thinking. Observation and data analysis are made in light of existing knowledge and thus cannot be totally objective. Importance of creativity. Unobservable entities
	Model Building: Piecing Together the Structure of DNA	Data do not tell scientists what to think. Much time often passes before a science idea becomes well-established. Complete objectivity is not possible. Science methods. Scientific models assist in understanding the natural world both by making sense of prior knowledge and guiding future research

(continued)

Table 28.1 (continued)

Stories		Overtly targeted NOS ideas/issues
	A Distinctly Human Quest: The Demise of Vitalism and the Search for Life's Origins	Prior knowledge impacts the interpretation of data. Scientific models assist in understanding the natural world both by making sense of prior knowledge and guiding future research. Methodological naturalism. Interplay of theoretical and empirical work. Science is a human endeavor
	The Realization of Global Warming	Scientific knowledge itself can impact society. Importance of coherence in data/ideas. Importance of theories. Science research is conducted in all sorts of settings, not just laboratories. Importance of pure and applied research. No universal scientific method
Chemistry	A Puzzle with Many Pieces: Development of the Periodic Table	Data do not tell scientists what to think. Importance of creativity and imagination. Importance of collaboration. Anomalies do not demand rejection of science ideas. Difference and relationships between laws and theories. No universal scientific method. Importance of ideas cohering
	Building Ideas: Developing a Model of the Atom	Science research is influenced by prior ways of thinking. Importance of creativity. Importance of basic science. That science ideas can be revised is a strength. Speculation is a crucial part of doing science. Importance of collaboration and creativity. Data does not tell scientists what to think
	Calorimetry: Creativity and Invention in Science	Interaction between basic science and technology. Data does not tell scientists what to think. Creativity and the development of ideas. Rather than a solitary activity, science requires collaboration. Much time is required to develop and accept science ideas.
	Conservation of Mass: Progress in Science Is Rarely Straightforward or Linear	Science research is influenced by prior ways of thinking. Complete objectivity is not possible. Data does not tell scientists what to think. Even well-established science ideas may change. That science ideas can be revised is a strength
	A Matter of Degrees: Conceptualizing Temperature and Heat	Interaction between science and technology. Meaning and value of "theory." Collaboration in science. Data do not tell scientists what to think. Creativity and the development of ideas. Much time is required to develop and accept science ideas. No universal scientific method
	Phlogiston and Explanation: The Problem of Combustion	Anomalies do not demand rejection of science ideas. Data must be interpreted; it does not tell scientists what to think. Science is a social endeavor. Role of theories. Scientific knowledge is a product and also guides thinking and research. Theory change

(continued)

Table 28.1 (continued)

Stories		Overtly targeted NOS ideas/issues
Geology	Continents: A Jigsaw Puzzle with no Mechanism	Impact of culture on science. Much time required to develop and accept science ideas. Data do not tell scientists what to think. Importance of creativity. What nature is like is not determined by voting. Prior knowledge impacts interpretation of data
	Data Do Not Speak: The Development of a Mechanism for Continental Drift	Establishment of scientific consensus. Complete objectivity is not possible. New science ideas are tied to prior ways of thinking. Data do not tell scientists what to think. What nature is like is not determined by voting. Difference and relationships between laws and theories
	Understanding Earth's Age: Early Efforts by Naturalists and Chronologists	Importance of collaboration. Data do not tell scientists what to think. Science and religion are not necessarily at odds with one another
	A Very Deep Question: Just How Old is Earth?	Scientific knowledge is a product and also guides process. Importance of creativity. Importance of coherence in data/ideas
	Ice Ages: An Alien Idea	Collaboration, competition, and much time go into the development and acceptance of science ideas. Even well-established science ideas may change. That science ideas can be revised is a strength. The wider culture impacts science thinking. No universal scientific method. Acceptance/rejection of ideas takes time
	Determining How Volcanic Activity Fit into the Greater System of the Earth	Data do not tell scientists what to think. Theory change is a complex process. The wider culture impacts science thinking. Prior knowledge impacts what is investigated and how data is interpreted
Physics	Pendulum Motion: The Value of Idealization in Science	Interaction of science and society. Difference and relationships between laws and theories. Data do not tell scientists what to think. Inventive character of science ideas. Purpose of science. Idealization and its value
	The Role of Theory: Pendulum, Time Measurement, and the Shape of the Earth	Rather than a solitary activity, science requires collaboration. Idealization and its value. Anomalies do not demand rejection of science ideas. Theory change
	Origins of Entropy: Cultural Influences on Scientific Knowledge	Differences and value of basic science, applied science, and technology. Idealization and its value. Prior knowledge impacts research, and thus scientists cannot be totally objective. Much time is required to develop and accept science ideas. Culture and subjectivity in science. Methodological naturalism

(continued)

Table 28.1 (continued)

Stories		Overtly targeted NOS ideas/issues
	Rejecting Common Sense: Science and Newton's First Law of Motion	Scientific thinking is often contrary to everyday ways of thinking. Collaboration in science. Scientific change has both a revolutionary and evolutionary character. No universal scientific method. Science ideas often emerge over time. Coherence of ideas. Even revolutionary science ideas are tied to prior ways of thinking.
	Conceptualizing Energy: Conservation of Mechanical Entergy and the Introduction of Potential Energy	Rather than a solitary activity, science requires collaboration. Differences and value of basic science, applied science, and technology. Science and religion are not necessarily at odds with one another. Coherence of ideas. Creativity and invention
	Worldviews, Universal Gravitation, and the Uneasy Acceptance of Action at a Distance	Differences and value of basic science, applied science, and technology. Science research is influenced by prior ways of thinking. No universal scientific method. Science and religion are not necessarily at odds with one another. Difference and relationships between laws and theories. Coherence of ideas

28.3 Strategies for Effectively Implementing the Project Stories

The Story Behind the Science project uses historical and contemporary episodes from authentic science research efforts to challenge common misconceptions regarding science and scientists, improve students' understanding of important NOS ideas, boost attitudes toward science and science classes, promote socio-scientific decision-making that is informed by the NOS, and bolster science content understanding. Achieving these important ends depends on how deeply students engage in and accurately interpret the stories. Because most students possess significant NOS misconceptions, without assistance they will likely miss or dismiss accurate NOS ideas in the stories and unconsciously modify aspects of what they read so that they fit their existing NOS misconceptions (Abd-El-Khalick and Lederman 2000; Tao 2003). For instance, Tao (2003) observed students working in pairs to interpret science stories with no assistance from their teacher and reported that:

> Since most students drew on the science stories for justifications of their views, the way they interpreted the science stories was crucial. Students' peer interactions showed that most of them were not fully aware of the overall theme of the stories; instead they attended to certain aspects that appealed to them and appeared to confirm and reinforce their inadequate views. (p. 167)

Thus, taking into account how people learn (Bransford et al. 2000), mediation strategies (Metz et al. 2007) appear in each project story to promote mental engagement and help students notice and consider more accurate NOS ideas. In each story, educative comments and questions are purposely placed at particular locations to overtly draw students' attention to the work and words of scientists that illustrate important NOS ideas, an important feature in promoting NOS conceptual change (Clough 2006). Effectively implementing the stories requires, at the very least, that instructors emphasize to students the importance of using the embedded comments and questions to more correctly interpret the stories and more accurately understand the NOS.

However, effectively implementing the project stories demands more than merely having students attend to the embedded comments and questions. Again, students come to these stories with deeply embedded NOS misconceptions, and that prior knowledge, like all prior knowledge, is used in making sense of experience, including the project stories. Thus, we created a NOS primer titled "Characteristics of science: Understanding scientists and their work" (https://storybehindthescience.org/pdf/characteristics.pdf). This primer was designed to be read prior to any stories because it overtly raises common NOS misconceptions and puts forward more accurate NOS ideas that students are encouraged to keep in mind as they read the project stories. The primer does not alter students' NOS misconceptions, but teachers report that assigning this reading along with the embedded questions plays an important role in raising students' interest and attention to NOS issues in the project stories and that many students convey in their responses a feeling of being cheated by having been taught NOS misconceptions in previous science classes.

While the NOS primer and the comments and questions embedded in the project stories are important for helping students more accurately interpret and understand NOS ideas, further assistance is required for achieving desired outcomes. If the readings and questions are merely assigned with no mention of them in class, students will understandably see them as not particularly important in the course. Thus, instructors should overtly address in class the connections between the stories and the content of the course, making clear important NOS ideas relevant to the development and acceptance of the science ideas being taught. That is, teachers should refer to the project stories and address what we know about the natural world, how we know, the complex and nonlinear path to that understanding, and what this means regarding the NOS. Some teachers choose to do this by asking questions during their presentation of information to engage students in the content and the NOS; others insert NOS issues in their science content presentation slides; while many do both. Additionally, as a science course progresses, NOS issues in a variety of stories should be compared. Doing so illustrates that how science is done, while having some common features, is impacted by context. The importance of these instructional strategies is that teachers are addressing both the science content and the NOS in class, conveying to students how they are intertwined, and that understanding both is valued.

Finally, for NOS teaching and learning to be taken seriously by many students, it must be part of determining students' performance in the course. Dall' Alba et al. (1993) make the important point that "assessment gives clear messages to students about what is important in the subject" (p. 633). Some teachers formatively assess students' answers to questions appearing in the stories, while others make clear the importance of understanding the NOS by including it on summative assessments. Clough (2011) provides examples of formative and summative NOS assessment questions, and NOS assessment assistance will soon be added to the support materials appearing on the project website.

The above suggestions share the following important features regarding effectively teaching the NOS. First, they have teachers consider NOS understanding as an overt learning outcome and purposely plan instruction to achieve that desired outcome. Second, each suggestion overtly draws students' attention to NOS issues and their importance for science literacy. Third, each recommendation mentally engages students in wrestling with NOS understanding. Finally, the NOS is addressed in a variety of contexts, which assists in promoting a deeper and more nuanced understanding of important NOS issues.

28.4 Classroom Example Illustrating the Use of Project Stories

Several studies have been conducted investigating story implementation and student outcomes. One study took place over the course of a semester in a post-secondary introductory biology course at a research-extensive university. The course met twice each week for 90 min each session and consisted primarily of biology majors. Early in the course, the professor had students read the Project NOS introduction mentioned earlier (https://storybehindthescience.org/pdf/characteristics.pdf) and answer the following two questions appearing at the end of the primer:

(a) What ideas about the characteristics of science surprised you?
(b) What new insight about science and scientists did you learn from this reading?

The professor read students' submitted responses and provided a small amount of credit if the answers reflected a serious consideration of the questions. During the 90-min class sessions, the professor regularly stops lecturing at the half-way point for 5–10 min to have students discuss with one another questions he poses and respond in some way (e.g., using clickers, verbally sharing what they discussed, etc.). After having assigned the NOS primer and two questions, during the next class meeting the NOS primer was the focus of the lecture interlude.

During the remainder of the semester, the following five stories and embedded questions were assigned at times that aligned with the science content being addressed:

- Understanding Earth's Age: Early Efforts by Naturalists and Chronologists
- A Very Deep Question: Just How Old is Earth?
- Creativity and Discovery: The Work of Gregor Mendel
- Adversity and Perseverance: Alfred Russel Wallace
- Charles Darwin: A Gentle Revolutionary

For each story, the embedded questions were assigned and reviewed by the instructor and a small amount of credit awarded for answers exhibiting serious effort. The two stories addressing Earth's age were together addressed during one lecture interlude, and the remaining three stories were addressed separately during lecture interludes. The professor of the course also periodically incorporated story and NOS points in his extensive presentation slide presentations during relevant science content lectures. All these strategies, along with the way he spoke about the NOS, made clear that it was an important learning expectation, and thus students were not surprised to see a few NOS items appear on the exams in the course.

28.5 Project Outcomes and Future Directions

Research results provide evidence that the stories promote improved NOS understanding and attitudes toward science careers. For instance, research findings from the biology course described above include the following (Clough et al. 2010):

- Statistically significant improvement between pre- and posttest scores regarding (a) the difference between theories and laws; (b) the role of imagination and creativity in science; (c) no universal scientific method; (d) science involves extensive collaboration; and (e) science and religion are not necessarily at odds with one another.
- Students report that the project stories portrayed science research in a way that was more interesting and increased their interest in science content and science as a career option.

Other studies have provided evidence that:

1. Students assigned the short stories in a biology course exhibited a statistically greater understanding of biological evolution than control group students.
2. Students assigned the short stories in an introductory geology course expressed more informed views regarding (a) the theory-laden nature of observations and the creativity required to account for data; (b) the variety of processes used in the construction of scientific knowledge; (c) why scientific data may be interpreted in various ways by different scientists; and (d) the roles that culture and society play in impacting the way scientific work is conducted and scientific ideas are constructed (Vanderlinden 2007).
3. Students generally make the intended sense of the stories, and this finding holds across various levels of story implementation (Kruse 2010; Vanderlinden 2007).

4. Science faculty see the project stories as complimentary to content instruction and conveying NOS ideas that assist students in understanding science concepts. The instructors also note that they are ill-equipped to create such stories on their own (Kruse 2010). Some instructors expressed shock at students' initial naive NOS views. They expressed increased interest in explicitly addressing NOS issues after seeing the results from short story implementation.

The perceived value of the project materials is illustrated by the more than 155,000 visits from 93,443 users to the project website during the past nine years.

Looking forward, additional instructional support on the project website will include sample presentation slides that make reference to the project stories and NOS ideas, additional instructional strategies for incorporating the stories in laboratory and field settings, and NOS assessment examples. We also are seeking funding to increase the number of stories for use at the post-secondary level and expand the project to include stories for secondary school science education efforts.

Humans have been called a "storytelling animal" (Gottschall 2012) in part because stories assist us in making sense of and bringing meaning to what we experience. The *Story Behind the Science* Project brings science and scientists to life in a way that helps students more accurately understand the nature of science and find it meaningful.

References

Abd-El-Khalick, F. (1999). Teaching science with history. *The Science Teacher, 66*(9), 18–22.

Abd-El-Khalick, F., & Lederman, N. G. (2000). The influence of history of science courses on students' views of nature of science. *Journal of Research in Science Teaching, 37*(10), 1057–1095.

Abd-El-Khalick, F., Myers, J. Y., Summers, R., Brunner, J., Waight, N., Wahbeh, N., Zeineddin, A. A., & Belarmino, J. (2017). A longitudinal analysis of the extent and manner of representations of nature of science in U.S. high school biology and physics textbooks. *Journal of Research in Science Teaching, 54*(1), 82–120.

Aydin, S., & Tortumlu, S. (2015). The analysis of the changes in integration of nature of science into Turkish high school chemistry textbooks: Is there any development? *Chemistry Education Research and Practice, 16*(14), 786–796.

Backhus, D. A., & Thompson, K. W. (2006). Addressing the nature of science in preservice science teacher preparation programs: Science educator perceptions. *Journal of Science Teacher Education, 17*(1), 65–81.

Banilower, E. R., Smith, P. S., Weiss, I. R., Malzahn, K. A., Campbell, K. M., & Weis, A. M. (2013). *Report of the 2012 national survey of science and mathematics education*. Chapel Hill: Horizon Research. Available at http://www.horizon-research.com/2012nssme/wp-content/uploads/2013/02/2012-NSSME-Full-Report1.pdf.

Bransford, J. D., Brown, A. L., & Cocking, R. R. (Eds.). (2000). *How people learn: Brain, mind, experience, and school*. Washington, DC.: National Academy Press.

Clough, M. P. (1997). Strategies and activities for initiating and maintaining pressure on students' naïve views concerning the nature of science. *Interchange, 28*(2-3), 191–204.

Clough, M. P. (2006). Learners' responses to the demands of conceptual change: Considerations for effective nature of science instruction. *Science & Education, 15*(5), 463–494.

Clough, M. P. (2011). The story behind the science: Bringing science and scientists to life in post-secondary science education. *Science & Education, 20*(7), 701–717.

Clough, M. P. & Olson, J. K. (2004). The nature of science: Always part of the science story. *The Science Teacher*, *71*(9), 28–31.

Clough, M. P., Herman, B. C., & Smith, J. A. R. (2010). *Seamlessly teaching science content and the nature of science: Impact of historical short stories on post-secondary biology students*. Association for Science Teacher Educators International Conference, Sacramento, CA, January 14–16. Available at http://www.storybehindthescience.org/research.html

Conant, J. B. (1957). *Harvard case histories in experimental science*. Cambridge: Harvard University Press.

Dall'Alba, G., Walsh, E., Bowden, J., Martin, E., Masters, G., Ramsden, P., & Stephanou, A. (1993). Textbook treatments and students' understanding of acceleration. *Journal of Research in Science Teaching, 30*(7), 621–635.

DeBoer, G. (1991). *A history of ideas in science education: Implications for practice*. New York: Teachers College Press.

DiGiuseppe, M. (2014). Representing nature of science in a science textbook: Exploring author-editor-publisher interactions. *International Journal of Science Education, 36*, 1061–1082.

Feng, J. (2012). The *inclusion of the nature of science and its elements in recent popular science writing for adults and young adults*. Unpublished doctoral dissertation, University of Arkansas, Fayetteville, AR.

Gottschall, J. (2012). *The storytelling animal: How stories make us human*. New York: Houghton Mifflin Harcourt.

Hagen, J., Allchin, D., & Singer, F. (1996). *Doing biology*. New York: HarperCollins

Heilbron, J. L. (2002). History in science education, with cautionary tales about the agreement of measurement and theory. *Science & Education, 11*(4), 321–331.

Höttecke, D., & Silva, C. C. (2011). Why implementing history and philosophy in school science education is a challenge: An analysis of obstacles. *Science & Education, 30*(3-4), 293–316.

Irwin, A. R. (2000). Historical case studies: Teaching the nature of science in context. *Science Education, 84*(1), 5–26.

Klopfer, L. E., & Cooley, W. W. (1963). The history of science cases for high schools in the development of student understanding of science and scientists. *Journal of Research in Science Teaching, 1*(1), 33–47.

Kruse, J. W. (2010). *Historical short stories in the post-secondary biology classroom: Investigation of instructor and student use and views*. Unpublished doctoral dissertation, Iowa State University. Available at https://storybehindthescience.org/research.html

Kuhn, T. S. (1970). *The structure of scientific revolutions*. Chicago: University of Chicago Press.

Matthews, M. R. (1994). *Science teaching: The role of history and philosophy of science*. New York: Routledge.

Metz, D., Klassen, S., McMillan, B., Clough, M., & Olson, J. (2007). Building a foundation for the use of historical narratives. *Science & Education, 16*(3-5), 313–334.

Olson, J. K., Tippett, C. D., Milford, T. M., Ohana, C., & Clough, M. P. (2015). Science teacher preparation in a North American context. *Journal of Science Teacher Education, 26*(1), 7–28.

Postman, N. (1995). *The end of education: Redefining the value of school*. New York: Vintage.

Stake, R. E., & Easley, J. A. (1978). *Case studies in science education*. Urbana-Champaign: University of Illinois. http://files.eric.ed.gov/fulltext/ED166059.pdf.

Stinner, A., McMillan, B. A., Metz, D., Jilek, J. M., & Klassen, S. (2003). *Science and Education, 12*(7), 617–643.

Tao, P. K. (2003). Eliciting and developing junior secondary students' understanding of the nature of science through a peer collaboration instruction in science stories. *International Journal of Science Education, 25*(2), 147–171.

Vanderlinden, D. W. (2007). *Teaching the content and context of science: The effect of using historical narratives to teach the nature of science and science content in an undergraduate introductory geology course*. Unpublished doctoral dissertation, Iowa State University. Available at http://www.storybehindthescience.org/research.html

Wei, B., Li, Y., & Chen, B. (2013). Representations of the nature of science in selected histories of science in the integrated science textbooks in China. *School Science and Mathematics, 113*(4), 170–179.

Weiss, I. R. (1993). Science teachers rely on the textbook. In R. E. Yager (Ed.), *What research says to the science teacher, volume seven: The science, technology, society movement*. National Science Teachers Association: Washington, DC.

Weiss, I. R., Pasley, J. D., Smith, P. S., Banilower, E. R., & Heck, D. J. (2003). *Looking inside the classroom: A study of K-12 mathematics and science education in the United States*. Chapel Hill: Horizon Research, Inc..

Chapter 29
A Typology of Approaches for the Use of History of Science in Science Instruction

William F. McComas

29.1 Introduction and Rationales for the Use of the History of Science (HOS) in Science Instruction

This book offers a variety of approaches designed to teach aspects of the nature of science. This chapter supports that theme by examining the role that might be played using the history of science in various forms in helping students understand aspects of the scientific enterprise. Here we will consider a proposed typology based on a review of the ways in which the history of science has been used in the past while considering what role these strategies might play in the future of science teaching.

The premise of this chapter is that history of science can be both a vehicle to convey important lessons about how science functions and a worthy destination. In other words, there is much to be gained from learning about the history of science because such a focus can humanize the sciences with their inclusion of the personalities that have shaped the direction and products of the scientific enterprise. In this fashion, HOS can reveal science as a "human endeavor," a frequently stated goal for science instruction. At the same time, carefully selected HOS content can also be used in another way to tell the tale of how science works, what its rules and traditions are, and how knowledge is established in the sciences.

This chapter has been adapted from a presentation at the 8th International Conference for the History of Science in Science Education Maresias, Sao Sebastiao, Brazil, August 16–19, 2010, and from an article appearing as W. F. McComas (2010). The history of science and the future of science education: A typology of approaches to the history of science in science instruction. In Kokkotas, P.V., Malamitsa, K.S., and Rizaki, A.A. (Eds.) Adapting Historical Knowledge Production to the Classroom (pp. 37–54). Rotterdam: Sense Publishers. Permission to adapt and include this chapter here has kindly been granted by the publisher

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_29

Advocacy for the inclusion of history of science in the science classroom is not new. More than a century and a half ago, the Duke of Argyll in his Presidential Address to the British Association for the Advancement of Science (1855) stated that, "What we want in the teaching of the young is not so much the mere results as the methods and, above all, the history of science," quoted in Matthews (1992), p. 11. In the United States, a hundred years later, the report Education for All American Youth (Educational Policies Commission, 1944) again raised the promise of the use of HOS stating:

> These scientists are thought of as living men [sic], facing difficult problems to which they do not know the answers, and confronting many obstacles rooted in ignorance and prejudice. In imagination, the students watch the scientists at work, and look particularly for the methods which they use in attacking their problems…

In 1947, the authors of the American Association for the Advancement of Science President's Scientific Research Board suggested that "Much more use should be made of the history of science with its adventure and dramatic action, which appeal strongly to young people's interests and arouse their imagination" (Steelman 1947, p. 86). Even today, the current National Science Education Standards (NRC 1996) include an explicit section on the history and nature of science primarily to illustrate the role played by humans, the nature of scientific knowledge, and historical perspectives of science. The Standards make the specific proposal that HOS may be useful in this regard with the recommendation that:

> Through the use of short stories, films, video, and other examples, elementary teachers can introduce interesting historical examples of men and women (including minorities and people with disabilities) who have made contributions to science. These stories can highlight how these scientists worked – that is, the questions, procedures, and contributions of diverse individuals to science and technology (p. 141).

> The introduction of historical examples will help students see the scientific enterprise as more philosophical, social and human (p. 170).

> Use of the history of science will show that "many individuals have contributed to the traditions of science … [and that] science has been practiced by different individuals in different cultures" … and reveal "how difficult it was for scientific innovators to break through the accepted ideas of their time to reach the conclusions that we currently take for granted." (p. 171)

Recommendations for the use of history of science in science instruction continue to be made and include those from Eichman (1996), Sherratt (1982, 1983), Matthews (1994), Rutherford (2001), and Hodson (2008). However, despite these recommendations, there is very little inclusion of the history of science either in textbooks or in classroom discourse. Unfortunately, most students only see science in its "final form," a label coined by Duschl (1990) describing the common situation in which teachers may share science conclusions with learners but rarely discuss the development of those conclusions. On this key point, Allchin adds that "History allows teachers to shift from the alienation of prescribed answers to the wonder or unsolved problems that motivate learning. The original context makes the reasons for doing science 'real'" (Allchin 2013, p. 30).

In the past 60 years, a variety of approaches to the inclusion of the history of science have been proposed, many of which will be discussed in subsequent sections of this paper. Accompanying these approaches is an impressive number of justifications for the use of HOS which are offered as a group in Table 29.1 but are drawn primarily from Sherratt (1982, 1983), Matthews (1994), Monk and Osborne (1997), Rasmussen (2007), Rudge and Howe (2009), and Wider (2006).

As examples of reasons to include history of science in the curriculum, some suggest that that using history of science increases students' knowledge of science content (Galili and Hazan 2000), while certain uses of HOS may assist students in forming connections between science content and other disciplines (Matthews 1994) and highlight the social side of science (Allchin 2013) and feels that this human aspect may promote students' desire to pursue a career in science. Ultimately some inclusion of HOS will help students see the rules of the game of science in context (Allen and Baker 2001).

Finally, we turn to the vital rationale that HOS can assist in learning about elements of NOS (Kolsto 2008; Irwin 2000) and established in several empirical studies that have investigated the impact of using HOS in supporting NOS understanding (Abd-El-Khalick and Lederman 2000a, b; Lin and Chen 2002; Rudge et al. 2014). As Adúriz-Bravo and Izquierdo-Aymerich (2009) point out:

Table 29.1 A list of rationales selected from a variety of sources supporting the use of the history of science in science teaching. Please note that no rank or ordering of importance is implied by the position of rationales on list

Inclusion of the history of science in science instruction potentially can:
1. Increase student motivation
2. Increase admiration for scientists
3. Help students develop better attitudes toward science
4. Humanize the sciences
5. Demonstrate that science has a history
6. Assist students in understanding and appreciating the interaction between science and society
7. Provide authentic illustrations for the way science functions
8. Reveal both the link and distinction between science and technology
9. Help to connect the science disciplines by showing the commonalities
10. Make instruction more challenging and thus will enhance reasoning
11. Provide opportunities for the development of higher order thinking skills
12. Contribute to a fuller understanding of basic science content
13. Help to reveal and dispel classic science misconceptions (this rationale is linked to what is called historical recapitulation in which some learners are seen to proceed through stages of misconceptions that are occasionally linked to incorrect ideas held by scientists in the past)
14. Provide an interdisciplinary link between science and other school subjects with an emphasis on bridging the gap between the "two cultures" (humanities and sciences)
15. Improve teacher education by helping teachers with their own science learning

> Key nature-of-science ideas can be taught to science teachers using the history of science as a meaningful vehicle. It has been shown that selected historical episodes, carefully reconstructed, can work as ‘settings’ that give meaning to rather abstract epistemological notions and promote their transference to other situations. (p.1179)

These rationales are drawn from a variety of sources; some are frequently mentioned by various authors, a few have been validated by research studies, while others are offered as suggestions for why HOS might play a role in science teaching. Readers should understand that the rationales provided do not pertain to all HOS instructional approaches but, as a group, represent broad support for the integration of HOS into science curricula for a variety of reasons.

In reviewing the various HOS instructional methods, there emerge as many distinct types as there are rationales for the incorporation of HOS in instruction. As we move forward in recommending the use of HOS, it is now necessary to provide some definitions about exactly what is meant by a HOS-based curriculum, a task that we will consider in the next section.

29.2 Why Propose a Classification Scheme for HOS Curriculum and Instructional Designs?

The classification plan or typology proposed here is designed to make explicit two central elements about HOS in the science classroom. First, a range of approaches and examples for ways the HOS may be used in science instruction exists, and the scheme proposed here makes this clear. In doing so, this typology builds in part on work by Allchin (1997). Second, this proposal makes explicit the reality that not all HOS educational approaches are the same; they are not all equally applicable into science instruction, and they make varying demands on teachers and students and will not necessarily produce the same impact on student learning and affect.

The author is aware that some will disagree with the distinctions made between types. Perhaps this proposal will elicit discussion and even debate. A NOS typology is a worthy and perhaps even necessary first step in establishing a framework for examining and discussing the roles, advantages, and disadvantages of each of these instructional types. One of the strongest reasons for the suggestion of this typology is to make the point that different approaches are very likely to have quite distinct challenges and rewards, to students and to teachers. The literature of science education is replete with suggestions that we should use the history of science in instruction but do so as if all HOS approaches are equally easy to implement and are equally beneficial. Clearly, that is not a valid conclusion. In research and development with respect to HOS in science teaching, we must now compare the effectiveness of varying approaches; to do that we must know what those varying approaches are.

This proposed typology is based on several factors starting with a review of actual HOS instructional models that have been developed and applied. This stands in preference to a discussion of all possible models. Even with this limitation acknowledged, it seems that almost every conceivable way to integrate HOS into science instruction has been attempted even as the degree of success of these attempts has generally not been measured well. Another element that factors into the classification plan offered here addresses the cognitive and affective impacts that are likely made by the method in question. One can assume that watching a film is different from reading an original manuscript. Even with this realization, there can be no a priori judgment about the ultimate impact that each presentation type might make. In fact, it seems reasonable to predict that impact may relate more to learners than to the HOS type. Some students may react more positively to some instructional approaches than others, while other learners may have quite a different response to the same technique.

The classification scheme is also based in part on the "distance" from the primary source material. The question is asked how much of the original work of the scientist is encountered by the student in comparison to the view of a scientist's achievement as interpreted by others. We will consider how much of the source material is encountered by students. This will become clear when examining, for instance, the distinction between having students read original works by Darwin and examining a case study on the history of evolution as a scientific principle. Finally, there is the distinction built into the typology which accounts for those approaches featuring a "hands-on" aspect of use of HOS. In some HOS approaches, students are asked to reenact or, in some other way, personally experience a noteworthy experiment or a series of experiments from the history of science.

Readers are cautioned not to assume that this typology was designed based on a hierarchy of effectiveness or rigor. This would be useful, but we generally do not have enough empirical evidence of the effectiveness with respect to any application of the history of science as an instructional technique. For instance, there is no implication that recreating a historical experiment is "better" than reading the report of that experiment in the words of the scientist who conducted the work.

The typology was not designed to represent "evolutionary" relationships linking one HOS approach or "type" to another such as one might find with a biological taxonomy. Rather, in developing this plan, the issue is one simple of difference. This typology defines and distinguishes one HOS approach from another with the presumption that these distinct approaches probably do impact students in diverse ways. At each level, examples are provided to illustrate either the approach itself or the source material for such an approach. No attempt has been made to include every illustration of every technique appearing in the literature, but the goal is to provide enough detail for readers to evaluate why one HOS instructional plan is distinct from another and why they are grouped as they are. Also, at each level, available research regarding the efficacy of the approach is provided.

One aspect of the use of history not captured by this proposal is that of integration and synergy. For instance, there is no classification provided for an approach which has students reenact a classic experiment *and* read the scientists' report. One could infer that such an approach would be different from the use of either method in isolation from the others that might be combined with it. There is also no useful way to categorize an approach that uses a video case study approach linking biographical elements of individual scientists such as Galileo with an overview of the science of mechanics. There may be some advantage in offering an additional level of classification for such “mixed” approaches, but here this has not been done. It seems that the basic challenge in the development of any typology is to avoid making everything a special case or providing such all-encompassing categories that no distinctions can be made; this, of course, is the classic dilemma of “lumping and splitting.” The plan provided here is offered simply to review and organize the various HOS approaches discovered thus far in a review of the literature and, as with all such plans, is open to critique and modification.

29.3 The Impact of HOS on Student Learning

At the inception of this project, one goal established was to associate studies of the impact of a strategy on student learning and/or affect. This task was ultimately impossible for several major reasons. First, even among the few high-quality empirical studies of history of science instruction, only a very few involved the use of a “pure” type. Second, very few studies provided enough detail of the nature of the intervention to gauge exactly what was done in the classroom. Finally, there are no “head-to-head” studies of the comparison of one type of HOS intervention and another.

Consider, for example, the study by Kim and Irving (2010) which explored the effectiveness of the contextualized history of science on student learning of NOS and genetics content knowledge in high school biology classroom. Here the experimental group was taught with historical curricular lessons, while the control group was taught with nonhistorical curricular lessons. The results showed that the experimental group developed better understanding in targeted aspects of NOS immediately after the intervention and retained the learning longer. However, both groups developed similar genetics knowledge. It is all but impossible to know what is meant by “historical curricular lessons,” and therefore it is impossible to categorize such lessons into a single type. It is laudable that researchers conducted a control-group study, but the measures are unclear, and the instructional method is reported in scant detail. However, we do have reason to be somewhat enthusiastic about the role of HOS in science instruction. However, what we really need is a more systematic study of the various modes by which students can learn about science through its history.

Following each of the proposed types is a section that summarizes the available research findings related to that special strategy. In too many cases, empirical findings are not available either to recommend or condemn such a strategy.

29.4 Proposed History of Science Typology of Instructional Approaches

To introduce the scope and scale of the proposed typology, consider the plan provided in Table 29.2. Each type is discussed in more detail in subsequent sections.

29.4.1 Type 1.0: First-Hand Interactions with Original Works (Teaching and Learning with Primary Sources)

This type essentially represents what is sometimes called the "Great Books" (Bloom 1994) approach to the history of science in which students read the actual accounts of science as written by the scientists themselves and then engage in guided discussions regarding what they have read. Such accounts are most likely limited to the original papers appearing in scientific journals but in rare cases might also consist of a review of working documents (such as laboratory notebooks, etc.). The classification at this level is further subdivided in recognition of the fact that students may

Table 29.2 A proposed typology for the kinds of HOS approaches applied in science instruction during the past 60 years

1.0 Interactions with original works (or selections) in the history of science (primary source)
1.1 Original works in their entirety (may include additional commentary)
1.2 Original works abstracted (may include additional commentary)
2.0 Case studies, stories, and other similar illustrations of the history of science (including those with original written materials)
2.1 Case studies (with original content)
2.2 Science stories
2.3 Shorter illustrations, vignettes, and examples
3.0 Biographies and autobiographies of scientists and their discoveries
3.1 Autobiography of a scientist
3.2 Biography of scientist (written)
3.3 Biography of scientist (passive dramatic presentations)
4.0 Book length presentations of some aspect of the history of science
4.1 Account of the general history of science
4.2 History of a scientific discipline
4.3 History of a scientific sub-discipline such as genetics, evolution, or quantum physics
4.4 History of a single discovery of event (such as an eclipse, the problem of longitude, appearance of Halley's Comet, etc.)
4.5 Accounts of classic experiments
5.0 Active role-playing and related activities with respect to historical personages
6.0 Textbook inclusions related to the history of science
7.0 Experimental reenactments and other "hands-on" approaches for engagement with historical aspects of science

read the original works in their entirety, may read abstracts of those works, may encounter a single paper, or may read sets of related papers from the same scientist or scientists associated with the same discovery or phenomenon.

Such original works are available in collections with commentaries such as found in the "critical editions" produced by some publishers. The *Norton Critical Editions* are good examples of such collections. In the critical edition of the discovery of the structure of DNA (Watson and Stent 1980), related papers are provided along with the original seminal work by Watson and Crick in Watson and Crick 1953.

Many scientists (Einstein and Darwin are good examples) are represented by extensive collections sometimes called "paper projects" that have so completely documented the life and times of individuals through their own writing that it is almost possible to know what a famous scientist was doing daily. This is certainly the case with Darwin (http://darwin-online.org.uk) whose works have been digitized and are easily accessible on line. Einstein's life has been similarly examined and chronicled.

In this "type," students (presumably with help from teachers) make sense of what they have read without relying on the interpretation provided by an interceding authority (such as a historian or other interpreter). In our increasingly wired world, it is now possible to download important papers and entire books making this HOS technique much easier than it was even a few years ago. Even so, teachers are reminded of the impact on the affective domain that may be made by actual objects and whether students could have the opportunity to see an original paper or an actual book from an important episode in the history of science (called realia). A visit to the rare books section of a library may be able to put students in "touch" with the history of science directly.

The additional levels of this typology are provided to make the distinction between works that are encountered in their original form and those encountered either as abstracts or with some additional commentary from experts. Illustrative of this approach are contributions such as *What's the Matter? Readings in Physics* (Whitfield 2007), *Biology: It's People and its Papers* (Baumel and Berger 1973), and Kampourakis and McComas (2009).

29.4.1.1 Impact on Students Through the Primary Source Approach

At least one US post-secondary institution (St. Johns College with campuses in Annapolis, Maryland, and Santa Fe, New Mexico) bases its curriculum on what is sometimes called the "Great Books approach," and the US Library of Congress has developed a robust set of web-based resources related to the use of primary sources (http://www.loc.gov/teachers/tps/) in instruction. Even with such support, little empirical work has been done to demonstrate what is likely to be learned by students through such means. The situation with respect to the learning of science as a subdomain of the two approaches just mentioned is even more bereft of research findings of support.

29.4.2 *Type 2.0: Case Studies, Stories, and Other Similar Illustrations of the History of Science (May Include Interaction with Original Written Materials and Laboratory Experiences)*

The case study or case method approach to instruction has been attempted in many disciplines, and science is no exception. For instance, there even exists a center for the use of case studies in the teaching of science (http://library.buffalo.edu/libraries/projects/cases/case.html) with an extensive set of such studies along with rationales for their use (Herreid 1994). The explicit use of the history of science has also been used in a case method format. Much of the early inspiration and advocacy for the use of the history of science in science instruction came from James B. Conant, scientist and president of Harvard University who expressed the view that "… *it is my contention that science can best be understood by laymen through close study of a few relatively simple case histories…*" (Conant 1947, p. 1).

Conant's passion for the use of history of science resulted in what is the most noteworthy example of the case approach, the Harvard Case Studies in Experimental Science (Conant and Nash 1948). The titles of the cases are provided in Table 29.3.

Later, Conant's student who then became fellow Harvard professor, Leo Klopfer (1964), adapted the case study approach for use in high schools with the *History of Science Cases (HOSC)*. Each of these units included the exploration of a major scientific idea through the examination of excerpts of historical documents and experimentation carried out either by students themselves or as a demonstration by the teacher (Lind 1979). Table 29.4 features a list of the nine titles proposed or developed for HOSC, each of which was represented by individual guides for teachers and students. The overarching goals for HOSC were to show students the methods used by scientists; how science advances and the conditions under which it flourishes; the personalities and human qualities of science; the interplay of social, economic, technological, and psychological factors with the progress of science; and the importance to science of accurate and accessible records, constantly improved instruments, and free communication between scientists (Klopfer 1964).

Table 29.3 The seven case studies included in the Harvard Cases in Experimental Science (Conant and Nash 1948)

Robert Boyle's Experiments in Pneumatics (64 pgs.)
The Overthrow of the Phlogiston Theory: The Chemical Revolution of 1775–1789 (52 pgs.)
The Early Development of the Concepts of Temperature and Heat; The Rise and Decline of the Caloric Theory (98 pgs.)
The Atomic-Molecular Theory (108 pgs.)
Plants and the Atmosphere (114 pgs.)
Pasteur's and Tyndall's Study of Spontaneous Generation (54 pgs.)
The Development of the Concept of Electric Charge: Electricity from the Greeks to Coulomb (98 pgs.)

Table 29.4 The cases developed (or proposed) for the *History of Science Cases (HOSC)* (Klopfer 1964). It is likely that some of these planned titles were never published, but that has been difficult to verify

The Cells of Life
The Chemistry of Fixed Air
Fraunhofer Lines
Frogs and Batteries
The Discovery of Halogen Elements
Air Pressure
The Sexuality of Plants
Rejection of Atomic Theory
The Speed of Light

Strategies within the "Stories" (2.2) category of the typology include "science stories," a term coined by Clough and Olson (2004) and further developed by Williams et al. (2010). Such narratives are written specifically for instructional purposes without much original material. Roach (1995) and Roach and Wandersee (1993) pioneered this approach in the use of short stories to share important lessons about science purpose-written stories. Sometimes scientists' dialogue is created for dramatic and instructional purposes. The goal is generally for students to learn a very specific lesson about how science works or about science content, and the stories have been crafted with such goals in mind. Current examples include those by Clough (2011) and Klassen (2006).

Even shorter HOS illustrations (Type 2.3) can be used to make points within existing lessons. An example of this approach would be for a teacher to tell the story of how Kekule imagined a chain of snakes one biting the tail of another to form a circle inspiring him to conclude that some hydrocarbons formed ring structures rather than the linear chains that was thought to be the only option. The story is perfectly suited for a chemistry teacher to make the point that creativity plays a key role in scientific discovery. Of course, this approach requires that teachers have such examples from which they may draw in instruction. McComas (2008) and Kampourakis and McComas (2009) (and included in this book as Chap. 30) further illustrate this technique with examples.

29.4.2.1 Impact on Students Through the Case Study/Story Approach

Many studies have been conducted to validate the case study/story approach with some of the earlier work done with the history of science case studies. Clough (2011) reports the results of an examination of the efficacy of using "science stories" in post-secondary geology instruction. He found that student understanding in areas such as creativity, the role and interpretation of data, the role of culture on science, etc. were enhanced with this technique when students were assessed following the assignment of stories related to the age of the earth and continental drift.

Viana and Porto (2010) describe the inclusion of HOS in science instruction using a case study focusing on the development of Dalton's atomic theory. Their rationale was that Dalton's work is a good example to show how scientific knowledge has been constructed in the past. Viana and Porto point out that the case study reveals "different aspects and dimensions of the scientific endeavor: the intellectual process of constructing scientific concepts, the nature of scientific knowledge, and even sociological aspects of science" (p. 86). Also, students may benefit from "gaining some insight into sociological aspects of science" (p. 87) as scientific knowledge is built on a social context and is influenced by people. In the case of Dalton's development of atomic theory, the conversations between Dalton, Henry, and Thomson allowed them to exchange ideas, which mutually influenced their works. This shows the collaborative work among scientists.

To allay the fears of those who think that historical case study approaches might be detrimental to the learning of traditional science content, Irwin (2000) shows this not to be a problem. His control group study of 14-year-old students learning about atomic theory using a historical orientation with one group and standard instruction in the other demonstrated that both groups had equal understanding of the basic science content at the end of the experience.

29.4.3 Type 3.0: Biographies and Autobiographies Detailing Scientists' Lives and Discoveries

Here, we find the life and research of scientists reported directly. The three types within this strategy will be discussed as a group even though there is likely a difference in impact on students linked to the way in which the information is delivered and to the "voice" of the author. There are countless examples of this HOS approach with first person narratives such as those by Charles Darwin (2002) *Autobiographies*, James Watson (1996) *The Double Helix*, and Richard Feynman (2005) *The Meaning of it All* and biographies such as *Galileo's Daughter* (Sobel 1999), *Einstein* (Isaacson 2007), Rosalind Franklin (Maddox 2002), and Issac Newton (Gleick 2003). Fingon and Fingon (2009) share an effectively updated version of the traditional strategy of having student's present scientists' biographies guided by a rubric for evaluation of these presentations. Dagher and Ford (2005) provide a cautionary note associated with the use of this strategy by reporting that some biographies written for younger children "were characterized by a relative absence of description of how scientists arrived at their knowledge…" (p. 377).

A "passive dramatic presentation" delivered on stage or in recorded format can be an adjunct to reading about the life and work of a scientist. An excellent example of this is the play QED by playwright Peter Parnell based on the life of Richard Feynman. This play brought science and its history to life for theatre-goers (and presumably for students too) as US actor Alan Alda (of *MASH* television fame) starred as the eccentric but brilliant physicist. The 1996 theatrical film *Infinity* dramatized Feynman's early life as a young scientist working on the development of the atomic bomb during the Manhattan Project. Teachers are cautioned in using such dramatizations; invariably "dramatic license" may result in a production that departs from the truth significantly or, at least, truncates the time in which discoveries are made and personalities interact. More recently, the National Geographic Society released a video series called Genius detailing the life and work of Albert Einstein. High-quality reenactments with strong production values can tell the story of a complex life in science such as Einstein's in a very engaging fashion.

There are many media products that have been produced exclusively for the education market that present the lives and work of scientists. Many offerings of the PBS NOVA series include historical recreations. Recent examples include *Einsteins' Big Idea*, *Darwin's Dangerous Idea*, *Newton's Dark Secret*, and Galileo's *Battle for the Heavens* (Public Broadcasting System). Another noteworthy example of this genre includes the series of eight modules from *MindWorks* (Becker 2000) that extend, complement, and enrich existing curricular materials on various subjects (Table 29.5) and the *Mechanical Universe Project* produced by the California Institute of Technology (1985) that provides explanations of many concepts in physics frequently accompanied by recreations of the actual personages, events, and experiments with actors in period costumes. Even without viewing the *Mechanical Universe* segments in their traditional fashion, it is be possible to extract these dramatic recreations as brief but engaging classroom illustrations of the history of science.

In conclusion, there seems to be no strategy reported in the literature for the way in which biography and autobiography can be used in the science classroom, but this approach to the history of science seems distinct from the others and, as such, demands to be a unique type.

29.4.3.1 Impact on Students Through the Biography Approach

With so many of the other strategies for the use of history of science in the classroom, little empirical data exists for its support. In one study, Lovedahl and Bricker (2006) asked fifth graders to read biographies of scientists hoping to expand their knowledge of what real scientists do. They found that the students were excited by the task since they could choose the scientists of personal interest. Students reported learning that "their" scientist was inspired at an early age (a point that many students connected to their own lives), doing science is not always easy, scientific ideas were not well accepted, and it took time before the scientist was successful and scientists do not give up. This last point was a stated instructional goal of the teacher.

Table 29.5 The video titles produced by Becker (2000) as part of the *MindWorks* project featuring recreations of:

Kinematics (Galileo: Falling Objects)
Dynamics (DuChatelet and Voltaire: Collisions)
Thermodynamics (Count Rumford: Heat)
Statics & Structures (Ferris and the Ferris Wheel)
Electricity & Magnetism (Woods: Communication/ Railway Telegraphy)
Light & Color (Newton and Wickins: Refraction of Light and Color)
Atoms & Matter (Curie and Huggins: Radioactivity)
Tomorrow's Challenges (Shirley and the Mars Pathfinder Mission)

29.4.4 Type 4.0: Book Length Presentations of Some Aspect of the History of Science

The impact of the strategies in this category relates to those just discussed but have been separated because of their focus. Instead of featuring the work of a single individual with emphasis on the “life, times, and work” of that individual from a biographical perspective, there are more generalized discussions. The subcategories have been arranged from those that are most generic (such as a narrative account of science itself as might be found in the three book series *The Story of Science* (Hakim 2005), to historical treatments of the history of a discipline (such as biology as exemplified by *The Epic History of Biology;* Serafini 2001) to a sub-discipline (such as molecular biology like *The Eighth Day of Creation;* Judson 1996), or even the history of a specific event (*Longitude;* Sobel 1995, is an excellent example of this genre)). A somewhat less related category, accounts of classic experiments, is also included here. There is little research to show how materials in this category of the history of science are used and what impact such use would have on students, but original materials have been applied successfully in a wide number of other areas of instruction (e.g., Bowler and Morus 2005).

29.4.4.1 Impact on Students Through the Book Approach

As with many of the other types of HOS approaches to the teaching of science, little targeted empirical research has been done to validate the use of this strategy, although testimonials abound.

29.4.5 Type 5.0: Role-Playing and Related Activities with Respect to Historical Personages

Admittedly, this level of the typology is the most tentative. Since there are a few inclusions in the literature to the use of direct and indirect role-playing activities in science instruction and because such techniques seem unique from the others provided here, this category was established. Instructional techniques in this category include those in which students take on the roles of historical personages in the history of science to act out, debate, or respond to questions as those persons. This may or may not involve having students dress up as the personages they portray. One could imagine students writing a play or otherwise reenacting the trial of Galileo more fully to understand and communicate the central issues of that debate. This would be characterized as a direct application of the use of role-playing in the history of science. A series of elaborate role-playing games collectively known as *Reacting to the Past* (http://reacting.barnard.edu) features several simulations related to the history of ideas and includes two from science including Charles Darwin and the Copley Medal and The Trial of Galileo. This site provides a useful model of the kind of role-playing featured at this classification in the HOS typology discussed here.

Alternatively, the teacher, or even an actor, might dress up as a famous scientist and take on the character of that person to give lectures and respond to questions *as* that person. Mendel, Darwin, Newton, Einstein, and other such distinctive scientists have all been the focus of this technique. Regrettably, nothing of substance has been found in the literature regarding the impact of the application of this strategy or on any robust discussion for how this might be used generally, but the technique would seem to hold some promise. Research should focus more intently on the impacts of these approaches. Having students engage in the role-playing activity (as active participants) is likely to make a different impact than watching the role-play (as passive participants).

29.4.5.1 Impact on Students Through the Role-Playing Approach

Unlike many of the other strategies discussed here, historical drama and role-playing have been both widely used and investigated (van den Berg 2009; Metcalfe et al. 1984 and Christofi and Davies 1991), and a variety of modules have been produced. For instance, Stinner and Tecihman (2003) produced a module based on "Lord Kelvin and the Age of the Earth Debate," Solomon (1989) contributed "Galileo's Trial," and Raman (1980) developed "Aristotle vs. Copernicus" among others. Christofi and Davies (1991) and Solomon et al. (1992) showed that role-playing improves student understanding of scientific concepts and ideas (as evidenced by students' test results) and nature of science knowledge. Duveen and Solomon (1994) developed a role-play based on the "Great Evolution Trial" to promote students' historical empathy.

Nonhistorical science drama seems a more common approach than historical ones and is recommended for teaching socio-scientific issues. Harwood et al. (2002) used a drama based on Senate hearings to debate global climate change in his college-level integrated science course for elementary pre-service students. The students became the characters of the special interest groups including the Sierra Club, Green Energy Society, Green Peace, environmental protection agency, representatives of the Governor's Office, and senators. Harwood and colleagues discovered that the role-play raised students' awareness of global warming. The students found role-playing to be useful teaching method and would use it in science classroom. From a conceptual understanding perspective, most students could give a list of consequences of global warming. However, students could not explain the cause and process of global warming in a scientific view.

29.4.6 *Type 6.0: Textbook Inclusions Related to the History of Science*

This category is offered to reflect a reality rather than an ideal state for the use of HOS in science teaching. Presently, relatively little NOS/HOS content is contained in textbooks and in classroom discussions. Typically, the few major scientific discoveries explicitly tied to those who made the contributions are discussed from such a human historical perspective. Galileo, Newton, Einstein, Darwin, and Watson/Crick are commonly mentioned even as the specifics of their work (often the most interesting and illustrative parts) are omitted. Several studies substantiate this point. Leite (2002) did a particularly complete job in describing how to look for the historical content in textbooks – physics in her case – and reported the finding that in the books examined the historical content generally failed to give students an adequate image of scientists and their work.

When scientists are mentioned, their contributions are limited to a few sentences, perhaps a picture, and birth and death dates – usually in a side bar in the textbook. Even this positioning almost guarantees that students and teachers alike will ignore the potential offered by such content. While this use of HOS is not particularly robust or compelling, it should be acknowledged as one way to account for as many possibilities of the incorporation of HOS as possible. One exception to the current state of inclusion of the history of science in science texts was the Project Physics curriculum developed in the 1960s and updated as *Physics, the Human Adventure* (Holton and Brush 2001). This project, which had as a coauthor science historian, Gerald Holton, deliberately included a rich historical treatment along with discussion of the science of physics (Holton 1969, 2003). While there have been studies of what history content is mentioned in science texts, there have been no comprehensive examinations of what use teachers make of such content or what impressions students have of this dimension of science teachers. It is probably not too great a conclusion to reach that HOS inclusion in science textbooks makes almost no impact on students or teachers unless it is explicitly woven into the curriculum. That is likely to happen only in the classrooms of teachers who already possess a strong interest in the subject.

29.4.6.1 Impact on Students Through the Textbook HOS Inclusion Approach

Several studies (for instance, Irwin 1996 and Summers et al. 2007) have analyzed the degree to which history of science and/or nature of science are represented in textbooks. Wang (1999), for instance, found that HOS topics are found scattered throughout many science textbooks, but the inclusion is typically very low level with scientists' birth and death dates accompanying brief biographical details. Unfortunately, there seem to be no studies of the impact of HOS inclusion in textbooks on student learning or attitudes.

Abd-El-Khalick et al. (2008) examined chemistry textbooks for their inclusion of NOS and concluded none of them included all the NOS elements emphasized in science education reform documents at the time. Niaz (1998) earlier analyzed chemistry textbooks for their inclusion of historical aspects of the atomic model and concluded that many useful aspects are missing. Fuselier et al. (2016) checked the representation of NOS in college evolution textbooks and found that sometimes there was mention of the social influence of evolution, and there was no explicit connection to NOS. Blachowicz (2009) adds that only 16% of textbooks discuss the historical origins of science.

29.4.7 Type 7.0: Experimental Reenactments and Other "Hands-On" Approaches for Engagement with Various Historical Aspects of Science

The final level in our proposed classification plan is that of the use of classic or historical experiments in the teaching of science. Of course, investigations such as the electrostatic effect of rubbing various fabrics on a glass rod are done frequently, but in most cases are not tied to specific persons or events in the history of the discovery of static electricity. The kinds of investigations that are considered for inclusion in this domain of the classification plan are those that are explicitly linked to the history of science. This aspect of history of science teaching is confounded by the reality that rarely are these hands-on approaches done in isolation from other techniques. Consider the *History of Science Cases*, discussed earlier in this paper; they too used engaged students in conducting experiments but blended this with reading about the scientist and the work being pursued. However, given the special nature of hands-on investigations and the unique impact that they may make, it seems reasonable to include such approaches in their own domain in the typology.

Resources of the use of this approach are relatively limited. Several books feature discussions of experiments that could be used as source material for either reading about or conducting (reconducting) some of these classic experiments. *The Ten Most Beautiful Experiments in Science* (Johnson 2009), *Great Experiments in Physics* (Shamos 1987), and *Great Scientific Experiments* (Harre 1981) are among the most useful. An extensive compendium of classroom-ready classic experiments covering all the sciences has been released as *Historical Science Experiments on File* (Walker 1993).

Many educators have used various permutations of experimental reenactments to support and perhaps enliven science learning. Kipnis (1996) developed what he calls the *historical investigative approach* and applied it to the study of optics and electricity. Peter Heerring (2000, 2003) has become quite expert in the construction of exact replicas of many important devices in the history of physics for use in the teacher education setting. As Chang (2011) points out, Elizabeth Cavicchi (2003, 2006, 2008, and 2009) has built on the observation of Crawford (1993) who discovered the strong impact on student that a historical connection could make. As she recounts, Crawford was engaged in an ion migration activity with students but her expertise in the work of Michael Faraday led her to bring Faraday's diaries to class to augment the basic lesson. She was able to show students that their work was identical to that of Faraday, but he had no underlying foundation of "ion" and "election" since those concepts had not yet been discovered and defined.

In 2008, Cavicchi reported that the historical reenactment had "value in recovering some of the interrelatedness inherent in the history and reintroducing the wonder of science phenomena to students today" (p. 717) but adds that "the history of science with its experimental legacy has yet to be plumbed as an educational resource for countering the fragmenting of science knowledge" (p. 719). Included in this approach are reports of replications of Galileo's experiments such as the inclined plan and acceleration from Settle (1961) to those of Palmieri (2008) more recently. We see Faraday again in the popular educational replication of his work in electromagnetism (e.g., Hottecke 2000, and Cavicchi 2006).

29.4.7.1 Impact on Students Through the Experimental Reenactment Approach

Scholars have investigated the impact of reenacting historical experiments on student learning (Allchin et al. 1999; Cavicchi 2008; and Seroglou et al. 1998), for example. To provide a specific example, consider the work of Dedes and Ravanis (Dedes and Ravanis 2009a, b) who used Kepler's experiment on geometrical optics model to teach image formation by extended light sources with 12- to 16-year-old Greek students. They began class by exploring students' existing knowledge and then showed experimental situations inspired by history of science. This led to conceptual conflict. The students tested their ideas by repeating Kepler's experiment. Two weeks later, the students were given task that were cognitively similar yet with different empirical content. They found that most students could make a correct prediction and justify the experimental results based on the scientific principle.

Chang (2011) follows this long tradition and offers the label of *complementary experiments*, which he feels can help recover lost scientific knowledge and extend what we do know about the original discovery. Within science instruction, these complementary experiments might help enrich the factual basis of science teaching, improve students' understanding of the nature of science, foster habits of original and critical inquiry, and attract students to science through a renewed sense of wonder.

29.5 Considering the History of Science in Science Education

Even if we agree on the general structure of the proposed typology, there are at least three additional major elements of HOS instruction worth considering. These would include some focus on the curriculum, pedagogy, and the affective domain. From a curricular perspective, it seems that HOS can only be effectively included in instruction if it is integrated within rather than appended to instruction, if HOS is somehow aligned with standards and other curricular goals, and if the focus of insighted derived from discussion of the history of science are featured in science assessment so that students take it seriously.

The pedagogical element is quite straightforward, and HOS-derived learning must be discussed explicitly (rather than implicitly) (Abd-El-Khalick and Lederman 2000a, b, Rudge and Howe (2009). As with nature of science itself, if the ideas that teachers hope to share through a history of science approach are only implied and hinted at, then it is likely that they will be ignored or missed by students. Lastly, there is an affective domain consideration. If the HOS content and instructional approach is not engaging, interesting, and developmentally appropriate, then it will likely not be responded to positively by students and, in turn, by teachers. If teachers value the incorporation of HOS in science instruction, then there is a very good possibility that the innovation will not last since students themselves will reject it. With the press of time and demands of coverage present on the science curriculum, ideas most likely to inform curriculum development are those that work.

29.6 Challenges Faced in Incorporating HOS in Science Instruction

There exists a long heritage both of advocacy for (McComas 1997) and innovation in the incorporation of the history of science in science instruction and even instructive criticism (Allchin 2003 and Kindi 2005). Yet, even with much scholarship and practical suggestions offered for the incorporation of history of science in science teaching, this approach to science teaching remains uncommon and generally untested in terms of impact and acceptance.

In order for a HOS focus in science teaching to find its place in science classrooms, science teacher education programs must be upgraded to include the effective use of HOS as part of generating appropriate Pedagogical Content Knowledge (PCK). Perhaps with guidance provided by a review of the typology, we must have a new focus on curriculum models for the effective and engaging inclusion of HOS into the science classroom. Finally, we should devote some of our research initiatives to the examination of the role and nature of HOS in the service of science teaching. Little has been done to determine the degree to which HOS should be included as an instructional imperative or in gauging the relative effectiveness of the various techniques for its use in school science teaching. We do not know what elements of HOS are effective for what science teaching purposes. We must consider the roles to be played by recapitulation (reenactment) vs. reconstruction (the writing of history for instructional purposes). We must also remain on guard that exposing students to "old" science may be problematic as we try to communicate "current science" (Lind 1979).

As we conclude this review of methodologies for the use of history of science, it seems clear that the inclusion of science history in science instruction should be a high priority. We must humanize sciences by revealing to students the diverse and interested people who have contributed to science in the past and continue daily. We should consider again the multitude of ways that educators and scholars have suggested that we incorporate HOS and consider which ones make sense in our new world of standards and benchmark tests. The challenge may be to integrate HOS in subtle, yet appropriate ways that do not make large demands on classroom time and on teacher knowledge. However, there is little doubt that the science curriculum would be enriched and enlivened if we can demonstrate to students where science comes from who has contributed to its development.

References

Abd-El-Khalick, F., & Lederman, N. (2000a). The influence of history of science courses on students' views of nature of science. *Journal of Research in Science Teaching, 37*, 1057–1095.

Abd-El-Khalick, F., & Lederman, N. G. (2000b). Improving science teachers' conceptions of the nature of science: A critical review of the literature. *International Journal of Science Education, 22*, 665–701.

Abd-El-Khalick, F., Waters, M., & Le, A. P. (2008). Representations of nature of science in high school chemistry textbooks over the past four decades. *Journal of Research in Science Teaching, 45*(7), 835–855.

Adúriz-Bravo, A., & Izquierdo-Aymerich, M. (2009). A research-informed instructional unit to teach the nature of science to pre-service science teachers. *Science & Education, 18*(9), 1177–1192.

Allchin, D. (1997). The power of history as a tool for teaching science. In A. Dally, T. Nielsen, & F. Reiss (Eds.), *History and philosophy of science: A means to better scientific literacy?* (pp. 70–98). Loccum: Evangelische Akadamie Loccum.

Allchin, D. (2003). Scientific myth conceptions. *Science & Education, 87*, 329–351.

Allchin, D. (2013). *Teaching the nature of science: Perspectives and resources*. Saint Paul: SHiPS Education Press.

Allchin, D., Anthony, E., Bristol, J., Dean, A., Hall, D., & Lieb, C. (1999). History of science -- with labs. *Science & Education, 8*, 619–632.

Allen, G., & Baker, J. (2001). *Biology: scientific process and social issues*. Maryland: Fitzgerald Science Press.

Baumel, H. B., & Berger, J. J. (1973). *Biology: It's people and its papers*. Washington, DC: National Science Teachers Association.

Becker, B. (2000). *Mindworks*. San Francisco: WestEd.

Blachowicz, J. (2009). How science textbooks treat scientific method: A philosopher's perspective. *The British Journal for the Philosophy of Science, 60*(2), 303–344.

Bloom, H. (1994). *The Western Canon: The books and school of the ages*. New York: Harcourt Brace & Company.

Bowler, P. J., & Morus, I. R. (2005). *Making modern science: A historical survey*. Chicago/New York: The University of Chicago Press.

California Institute of Technology. (1985). *The mechanical universe and beyond*. Retrieved April 30, 2009 from http://www.learner.org/resources

Cavicchi, E. M. (2003). Experiences with the magnetism of conducting loops: Historical instruments, experimental replications, and productive confusions. *American Journal of Physics, 71*, 156–167.

Cavicchi, E. M. (2006). Faraday and Piaget: Experimenting in relation with the world. *Perspectives on Science, 14*(1), 66–96.

Cavicchi, E. M. (2008). Historical experiments in students' hands: Unfragmenting science through action and history. *Science & Education, 17*, 717–749.

Cavicchi, E. M. (2009). Exploring mirrors, recreating science and history, becoming a class community. *The New Educator, 5*, 249–273.

Chang, H. (2011). How historical experiments can improve scientific knowledge and science education: The cases of boiling water and electrochemistry. *Science & Education, 20*(3–4), 317–341.

Christofi, C., & Davies, M. (1991). Science through Drama. *Education in Science, 141*, 28–29.

Clough, M. P. (2011). The story behind the science: Bringing science and scientists to life in post-secondary science education. *Science & Education, 20*(7), 701–717.

Clough, M. P., & Olson, J. K. (2004). The nature of science: Always part of the science story. *The Science Teacher, 71*, 28–31.

Conant, J. B. (1947). *On understanding science*. New Haven: Yale University Press.

Conant, J. B., & Nash, L. K. (1948). *Harvard case histories in experimental science volumes I and II*. Cambridge, MA: Harvard University Press.

Crawford, E. (1993). A critique of curriculum reform: Using history to develop thinking. *Physics Education, 28*, 204–208.

Dagher, Z., & Ford, D. (2005). How are scientists portrayed in children's science biographies. *Science & Education, 14*, 377–393.

Darwin, C. (2002). *Autobiographies*. New York: Penguin Group.

Dedes, C., & Ravanis, K. (2009a). History of science and conceptual change: The formation of shadows by extended light sources. *Science & Education, 18*, 1135–1151.

Dedes, C., & Ravanis, K. (2009b). Teaching image formation by extended light sources. *Research in Science Education, 39*, 57–73.

Duschl, R. A. (1990). *Restructuring science education: The importance of theories and their development*. New York: Teachers College Press.

Duveen, J., & Solomon, J. (1994). The Great evolution trial: Use of role-play in the classroom. *Journal of Research in Science Teaching, 31*(5), 575–582.

Educational Policies Commission. (1944). *Educational policies Commission report on education of all American youth*. Washington, DC: National Education Association.

Eichman, P. (1996). Using history to teach biology. *The American Biology Teacher, 58*, 200–202.

Feynman, R. P. (2005). *The meaning of it all: Thoughts of a citizen scientist*. New York: Basic Books.

Fingon, J. C., & Fingon, S. D. (2009). What about Albert Einstein? Using biographies to promote students' scientific thinking. *Science Scope, 32*, 51–55.

Fuselier, L. C., Jackson, J., & Stoiko, R. (2016). Social and Rational: The presentation of nature of science and the uptake of change in evolution textbooks. *Science Education, 100*(2), 239–265.

Galili, I., & Hazan, A. (2000). The influence of an historically oriented course on students' content knowledge in optics evaluated by means of facets-schemes analysis'. *Physics Education Research: A Supplement to the American Journal of Physics, 68*(7), S3–S15.

Gleick, J. (2003). *Isaac Newton*. New York: Pantheon Books.

Hakim, J. (2005). *The story of science: Newton at the center*. Arlington: NSTA Press.

Harre, R. (1981). *Great scientific experiments. Twenty experiments that changed our view of the world*. Chelmsford: Courier Dover Publications.

Harwood, W. S., MaKinster, J. G., Cruz, L., & Gabel, D. (2002). Acting out science: Using senate hearings to debate global climate change. *Journal of college science teaching, 31*, 442–447.

Heering, P. (2000). Getting shocks: Teaching secondary school physics through history. *Science & Education, 9*, 363–373.

Heering, P. (2003). History-science-epistemology: On the use of historical experiments in physics teacher training. In W. F. McComas (Ed.), In *Proceeding of the 6th international history, philosophy and science teaching group meeting (Denver, USA)* [File 58 on CD ROM from IHPST.ORG].

Herreid, C. F. (1994). Case studies in science-A novel method of science education. *Journal of College Science Teaching, 23*, 221–229.

Hodson, D. (2008). *Towards scientific literacy: A teacher's guide to the history, philosophy and sociology of science*. Rotterdam: Sense Publishers.

Holton, G. (1969). Harvard project physics: A report on its aims and current status. *Physics Education, 4*, 19–25.

Holton, G. (2003). The Project Physics Course, then and now. *Science & Education, 12*, 779–785.

Holton, G., & Brush, S. G. (2001). *Physics, the human adventure: From Copernicus to Einstein and beyond*. New Brunswick: Rutgers University Press.

Hottecke, D. (2000). How and what can we learn from replicating historical experiments? A case study. *Science & Education, 9*, 342–362.

Irwin, A. R. (1996). A survey of the historical aspects of science in school textbooks. *School science review, 78*, 101–107.

Irwin, A. R. (2000). Historical case studies: teaching the nature of science in context. *Science Education, 84*, 5–26.

Isaacson, W. (2007). *Einstein: His life and universe*. New York: Simon and Schuster.

Johnson, G. (2009). *The ten most beautiful experiments*. New York: Knopf.

Judson, H. F. (1996). *The eighth day of creation*. Cold Springs Harbor: Cold Springs Harbor Laboratory Press.

Kampourakis, K., & McComas, W. F. (2009). Using the history of biology to illustrate core nature of science ideas. In: *Proceedings of the 5th Greek conference on history, philosophy & teaching of natural sciences: The great scientific theories in the teaching of natural sciences, Nicosia, Cyprus*.

Kim, S. Y., & Irving, K. E. (2010). History of science as an instructional context: Student learning in genetics and nature of science. *Science & Education, 19*, 187–215.

Kindi, V. (2005). Should science teaching involve the history of science? An assessment of Kuhn's view. *Science & Education, 14*, 721–731.

Kipnis, N. (1996). The "historical-investigative" approach to teaching science. *Science & Education, 5*, 277–292.

Klassen, S. (2006). The application of historical narrative in science learning: The Atlantic Cable Story. *Science & Education, 16*, 335–352.

Klopfer, L. E. (1964). *History of Science Cases (HOSC)*. Chicago: Science Research Associates.

Kolsto, S. D. (2008). Science education for democratic citizenship through the history of science. *Science & Education, 17*(8/9), 977–997.

Leite, L. (2002). History of science in science education: Development and validation of a checklist for analyzing the historical content of science textbooks. *Science & Education, 11*, 353–359.

Lin, H. S., & Chen, C. C. (2002). Promoting preservice chemistry teachers' understanding about the nature of science through history. *Journal of Research in Science Teaching, 39*(9), 773–792.

Lind, G. (1979). The history of science cases (HOSC): Nine units of instruction in the history of science. *European Journal of Science Education, 1*(3), 293–299.

Lovedahl, A. N., & Bricker, P. (2006). Using biographies in science class. *Science and Children, 44*, 38–43.

Maddox, B. (2002). *Rosalind Franklin: The dark lady of DNA*. New York: HarperCollins.

Matthews, M. R. (1992). History, philosophy and science teaching: The present rapprochement. *Science & Education, 1*(1), 11–48.

Matthews, M. R. (1994). *Science teaching, the role of history and philosophy of science*. New York: Routledge.

McComas, W. F. (1997). The discovery and nature of evolution by natural selection: Misconceptions and lessons learned from the history of science. *American Biology Teacher, 59*, 492–500.

McComas, W. F. (2008). Seeking historical examples to illustrate key aspects of the nature of science. *Science & Education, 17*(2/3), 249–263.

Metcalfe, R. J. A., et al. (1984). Teaching Science through Drama: An Empirical Investigation. *Research in Science and Technological Education, 2*, 77–81.

Monk, M., & Osborne, J. (1997). Placing the history and philosophy of science on the curriculum: a model for the development of pedagogy. *Science Education, 81*(4), 405–424.

National Research Council. (1996). *The national science education standards*. Washington, DC: National Academy Press.

Niaz, M. (1998). From cathode rays to alpha particles to quantum of action: A rational reconstruction of structure of the atom and its implications for chemistry textbooks. *Science Education, 82*, 527–552.

Palmieri, P. (2008). *Reenacting Galileo's experiments: Rediscovering the techniques of seventeenth-century science*. Lewiston: The Edwin Mellen Press.

Public Broadcasting System (PBS). Science programming on air and online. http://pbs.org/wgbh.nova/

Raman, V. V. (1980). Teaching Aristotelian Physics through a Dialogue. *Physics Teacher, 18*(8), 580–583.

Rasmussen, S. C. (2007). The history of science as a tool to identify and confront pseudoscience. *Journal of Chemical Education, 84*, 949–951.

Roach, L. E. (1995). Putting people back in science: Using historical vignettes. *School Science and Mathematics, 95*, 365–370.

Roach, L. E., & Wandersee, J. H. (1993). Short story science. *The Science Teacher, 60*, 18–21.

Rudge, D. W., & Howe, E. M. (2009). An explicit and reflective approach to the use of history to promote understanding of the nature of science. *Science & Education, 18*, 561–580.

Rudge, D. W., Cassidy, D. P., Fulford, J. M., & Howe, E. M. (2014). Changes observed in views of nature of science during a historically based unit. *Science & Education, 23*(9), 1879–1909.

Rutherford, J. (2001). Fostering the history of science in American science education. *Science & Education, 10*, *569–580*.

Serafini, A. (2001). *The epic history of biology*. Boulder: Perseus Publishing Company.

Seroglou, F., Koumaras, P., & Tselfes, V. (1998). History of science and instructional design: the case of electromagnetism. *Science & Education, 7*, 261–280.

Settle, T. B. (1961). An experiment in the history of science. *Science, 33*, 19–23.

Shamos, M. (1987). *Great experiments in physics*. New York: Dover Publications.

Sherratt, W. J. (1982). History of science in the science curriculum: An historical perspective Part I: Early interest and role advocated. *School Science Review, 64*, 225–236.

Sherratt, W. J. (1983). History of science in the science curriculum: An historical perspective. Part II: Interest shown by teachers. *School Science Review, 64*, 418–424.

Sobel, D. (1995). *Longitude: The true story of a lone genius who solved the greatest problem of his time*. New York: Walker and Co..

Sobel, D. (1999). *Galileo's daughter: A historical memoir of science, faith, and love*. New York: Walker and Co..

Solomon, J. (1989). The retrial of Galileo. In: *Paper presented at the The First International History, Philosophy of Science and Science Teaching Conference Tallahassee*.

Solomon, J., Duveen, J., Scott, L., & MaCarthy, S. (1992). Teaching about the Nature of Science through History: Action Research in the Classroom. *Journal of Research in Science Teaching, 29*(4), 409–421.

Steelman, J. R. (1947). *Manpower for research: volume 4 of science and public policy*. Washington, DC: U.S. Government Printing Office.

Stinner, A., & Tecihman, J. (2003). Lord Kelvin and the Age-of-the-Earth Debate: A dramatization. *Science and Education, 12*(2), 213–228.

Summers, G., Decker, T., & Barrow, L. (2007). The treatment of geological time and the history of life on Earth in high school biology textbooks. *American biology teacher, 69*, 401–405.

van den Berg, E. (2009). Theater in Physics Teacher Education. *Physics Teacher, 47*(6), 350–352.

Viana, H. E. B., & Porto, P. A. (2010). The development of Dalton's atomic theory as a case study in the history of science: Reflections for educators in chemistry. *Science and Education, 19*, 75–90.

Walker, R. (1993). *Historical science experiments on file*. New York: Facts on File, Inc..

Wang, H. A. (1999). *A content analysis of the history of science in the national science education standards and four secondary science textbooks*. ERIC ED431608.

Watson, J. D. (1996). *The Double Helix: A personal account of the discovery of the structure of DNA*. New York: Simon and Schuster.

Watson, J. D., & Crick, F. H. C. (1953). Molecular structure of nucleic acids: A structure for deoxyribose nucleic acid. *Nature, 171*, 737–738.

Watson, J. D., & Stent, G. S. (Eds.). (1980). *Double helix: A personal account of the discovery of the structure of DNA*. New York: W.W. Norton and Company.

Whitfield, D. H. (2007). *What's the matter? Readings in physics*. Chicago: The Great Books Foundation.

Wider, W. (2006). Science as story communicating the nature of science through historical perspectives on science. *American Biology Teacher, 68*, 200–205.

Williams, B., Clough, M. P., Stanley, M., Dawson, J. P., & Cervato, C. (2010). *A very deep question: Just how old is Earth?* http://www.storybehindthescience.org/pdf/earthsage2.pdf. *The story behind the science: Bring science and scientists to life project website*, http://www.storybehindthescience.org

Chapter 30
Using Anecdotes from the History of Biology, Chemistry, Geology, and Physics to Illustrate General Aspects of Nature of Science

William F. McComas and Kostas Kampourakis

30.1 Introduction to the History of Science Anecdote Approach

There the goal of this chapter is to provide a method by which teachers can weave NOS lessons into their traditional focus on science content using a teaching tool called the *History of Science Anecdote Approach*. In this plan, the teacher uses a relevant story from the history of science to teach both a history of science (HOS) lesson and one related to NOS derived from that historical anecdote. This chapter features a "ready-to-use" guide to teach about each of the key NOS aspects that are discussed in detail in Chap. 3, each linked here to illustrations from the history of science in geology, biology, chemistry, and physics. Readers are encouraged to review the key notions and their definitions since, to avoid redundancy, they are not discussed here.

To produce these examples of NOS and HOS, we have reviewed many accessible books written by professional historians of science (such as Bowler and Morus 2005; Dear 2006; Fara 2009). The illustrations presented here could be incorporated into classrooms in a variety of ways. Teachers could simply share them with students when they are relevant to an aspect of instruction. The stories could be used in a

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Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_30

group focusing on the overall nature of science. Alternatively, they could be framed as the foundation of an assignment, in which students work in small groups to expand these stories by exploring their full context and the personalities involved. Students could then present their findings to the class and show how the nature of science is illustrated. In fact, many of these stories can be used to illustrate more than the single NOS tenet to which each one of them is linked here. Teachers are encouraged to examine the overview of the stories, and the respective NOS aspects to which they apply are presented in Table 30.1 with more detail provided in the following discussion.

Teachers are encouraged to review the illustrations provided for their science discipline and share these examples with students throughout the year. If teachers from various science disciplines were to use the NOS illustrations pertaining to their science with the same group of students, it is very likely that students' NOS understanding could be greatly enhanced. Although teaching HOS to students and preservice teachers is not sufficient for enhancing their NOS views, explicitly addressing specific NOS aspects during HOS courses might enhance that effectiveness (Abd-El-Khalick and Lederman 2000).

30.2 Science Relies on Empirical Evidence

Science requires that researchers provide data that justify all conclusions or form the basis for explanations. Data become evidence that supports or does not support some hypothesis or theory when it is seen in their light. In addition to experiments, equally important are observations, model construction, and mathematical analyses. In some cases, scientists may use a combination of methods, but in all cases, they look for empirical evidence to support a theory or to develop an explanation. The examples that follow show how empirical evidence was crucial in providing support for scientific theories or even for opening new fields of scientific endeavor.

30.2.1 Biology

Experimental evidence was important for the emergence of classical genetics during 1910–1915, through the research by Thomas Hunt Morgan and his group, who linked "Mendel's laws" to chromosomes. Morgan's group conducted experiments with Drosophila (fruit fly) and showed that genes could be envisioned as sections of chromosomes that were related to characters in the organism. A careful breeding program and statistical analyses of the experimental results showed that changes in particular genes could account for changes in particular phenotypes in Drosophila. The Morgan team's further research established that each chromosome carried a collection of genes. They also studied the production of new genetic characters by mutations and showed that these could be caused by external factors such as radiation.

Table 30.1 An overview of the historical examples presented here and their relation to general NOS aspects

General NOS Aspect	Biology	Chemistry	Geology	Physics
1. Science relies on empirical evidence	The experimental evidence produced by Morgan and his group on the mechanisms of heredity and mutations	Boyle's experiments on the nature and constitution of the air to find evidence for the existence of atoms	Hooke finding evidence to show that fossils originated from organisms that lived in the past and that extinction was possible	Eddington testing and finding evidence in support of Einstein's general relativity theory
2. There is no single scientific method	Watson and Crick's double-helix model for the structure of DNA, which relied on data accumulated by others	Rutherford and Bohr suggesting the atom model, with the latter building on the work of the former	Wegener's theory of continental drift that was plausible but required evidence for it to be accepted	Hubble and the separate-galaxies theory, based on calculations of the distances of particular stars
3. Laws and theories are distinct kinds of scientific knowledge	Mendel's laws and the missing theory of heredity at the time	Mendeleev's idea of the periodic table of elements and the atomic theory that later explained it	Hess, the theory of plate tectonics, and the laws of physics	Newton's laws of motion and gravity, and the explanation for why the respective phenomena occurred in the way they did
4. Science is a creative process	Darwin, natural selection, and the analogy from artificial selection	Lavoisier and his novel chemical nomenclature	Wegener's theory of continental drift and the torn-paper analogy	Carnot's analogy between water mill and caloric
5. Science has a subjective component	Pasteur, a devout Catholic, conducting experiments to show that spontaneous generation is impossible	Van Helmont's experiment to prove that water was the only element	Hutton's and Lyell's deism as a motivation for uniformitarianism	Kepler initially believing that the heavens must be governed by geometry
6. There are historical, cultural, political, and social influences on science	Darwin not publishing after the reaction to the *Vestiges,* then proceeding to publication in order not to lose priority to Wallace	Lavoisier and the experiments that led to the abandonment of the phlogiston theory while at the Paris Arsenal	Wegener, a geophysicist, rejected as an outsider by the community of professional geologists	Galileo's, Brahe's, and Kepler's astronomical works being sustained by royal or aristocratic patronage

(continued)

Table 30.1 (continued)

General NOS Aspect	Biology	Chemistry	Geology	Physics
7. Science and technology influence each other	The development of the cell theory by Schleiden and Schwann following the improvement of microscopes	Becher's investigations on the origin of minerals, carried out in order to improve mining technology	Blackett's magnetometer for mines used to measure magnetism in rocks, providing evidence for the theory of continental drift	Scientists working in close cooperation with engineers during the Manhattan Project
8. Scientific knowledge is tentative	Cuvier's conclusions that questioned Lamarck's evolutionary ideas eventually came to support evolution	Stahl's phlogiston theory, Priestley's dephlogisticated air, and Lavoisier's oxygen	Humboldt rejecting Neptunism and explaining geological changes based on earth movements	Thomson showing that Hertz's conclusions were wrong and discovering the electron
9. Science cannot answer all questions	Owen suggesting the existence of a divine plan in nature	Priestley, aerial economy, and social order	Buckland's seeking evidence for Noah's flood	Joule's experiments as providing evidence of the way God had organized creation

More importantly, they showed that not all mutations were harmful and that they could be a source of new variation, which is necessary for the evolution of a population by natural selection (Bowler and Morus 2005, p. 203; Fara 2009, pp. 341–343). In this case, experimental evidence was crucial for the emergence of a whole new research field.

30.2.2 *Chemistry*

Robert Boyle was greatly influenced by Francis Bacon and his view that investigations should begin by collecting as much empirical data as possible and then trying to explain the observations and not by first having an idea and then looking for evidence to support it. Boyle believed that everything was made up of matter in motion, and he used air-pump experiments to establish many claims about the constitution and nature of the air. Boyle, and his assistant, Robert Hooke, built the first working air pump in the late 1650s. Although there were several technical problems and although Boyle knew that it was not self-evident that the way the air behaved inside the pump accurately reflected its natural behavior, he produced detailed reports of his observations during the experiments. He also carried out his experiments in public so that people could witness the results. Based on these experiments, Boyle argued that the air was made up of spring-like particles and that it was because of their properties that the air could resist any force exerted on it and later expand when the force was removed. Again, experimental evidence was important for advancing a new field, though even Boyle himself was skeptical about what might be inferred from his experiments (Bowler and Morus 2005, pp. 37, 44–45, 60; Fara 2009, p. 161).

30.2.3 Geology

Experiments are not the only way to obtain empirical evidence. In the 1660s, Robert Hooke (and anatomist Nicholas Steno) correctly identified fossils as the remains of organisms. At that time, it was thought that fossils were just stones that had somehow come to look like organisms. Hooke successfully showed that fossil wood was like its modern equivalent under the microscope. He also noted the appearance of fossils within layers of rock that seemed to have been deposited under water, although they were exposed on dry land. One possible explanation for such observations had been that all the sedimentary rocks were laid down from sediment created during Noah's flood. However, Hooke had noticed that a whole sequence of events seemed to have taken place and formed the structure of the Earth's surface. The characteristics of the strata gave the impression that they had been extensively transformed after being laid down. Hooke even postulated earthquakes that had raised new areas of land from the bottom of the oceans to the surface. The observation that fossils seemed to represent organisms that were no longer alive raised the possibility that species might have become extinct in the course of time (Bowler and Morus 2005, pp. 106–108). In this case, careful and detailed observation provided new insights crucial for understanding the history of life.

30.2.4 Physics

Albert Einstein suggested in 1907 that his theory of relativity might be expanded into a theory of gravitation. This theory and its implications were fully worked out in 1915. Einstein noted that his theory was open to empirical confirmation, having already demonstrated that it could be used to account for anomalies in the orbit of Mercury, which could not be explained by the Newtonian gravitational theory. Arthur Eddington attempted to test this theory—in particular—Einstein's prediction of light bending in a gravitational field. He aimed to use the 1919 solar eclipse to photograph the positions of stars around the Sun's corona that would normally be blocked by its light. By comparing these positions to those the stars appeared to occupy when the Sun was not in their part of the sky, he expected to determine whether the Sun's gravitational field caused light to bend. The results supported the general relativity theory, although not immediately and not as conclusively as

Eddington had suggested (Bowler and Morus 2005, pp. 263–264; Fara 2009, pp. 298–299). No matter how well Einstein's theory was established in theoretical terms, it could become widely accepted only after empirical evidence would have been obtained through observation.

The common, underlying idea in these historical examples is that empirical evidence is crucial to support, and later establish, theoretical claims. No matter how logical or sophisticated one's claims are, they can be widely accepted only insofar as adequate evidence is found that supports them. This, of course, is not a linear or straightforward process, and contradictory evidence may always be found. Yet only empirical evidence, ideally stemming from independent sources, can suffice to establish theoretical claims in science.

30.3 Historical Examples Demonstrating That There Are Shared Methods But No Step-by-Step Method Used by All Scientists

Although there certainly are some common features in the practice of science, there is no universal, step-by-step scientific method. Of course, at some point in any investigation, scientists will define the problem, may (or may not) form a hypothesis, collect data, make conclusions, and report results. The examples that follow show that doing science is a mixture of performing standard processes, such as doing experiments, interpreting the data of others (in the case of Watson and Crick), and making careful observations. However, quite often, scientists come to conclusions in highly personal ways.

30.3.1 Biology

In 1953, James Watson and Francis Crick proposed the double-helical model of DNA, without doing a single experiment themselves. Instead they interpreted, appropriately, the experimental evidence accumulated by other researchers. Erwin Chargaff had earlier shown that any DNA molecule contained equal proportions of adenine and thymine, as well as of guanine and cytosine. John Griffith had pointed out that adenine and thymine, as well as guanine and cytosine, could fit together, linking up through hydrogen bonds. Maurice Wilkins and Rosalind Franklin had performed X-ray diffraction studies of DNA, suggesting a spiral arrangement of the molecule. In many ways, the photographs taken by Franklin were the key piece of evidence that Watson and Crick combined with the earlier findings to come up with the model of the double-helix structure of DNA. They built actual models of the molecule, having been inspired by Linus Pauling's model-building of molecules. They were lucky and insightful, and eventually they came up with an appropriate model, although it took several years and many other scientists to work out all the details (Bowler and Morus 2005, pp. 206–297; Fara 2009, pp. 375–381). Overall, Watson and Crick proposed the model of the double helix for the structure of DNA by relying on evidence accumulated by other researchers.

30.3.2 Chemistry

In 1911, Ernest Rutherford announced his model of the atom, based on his experiments on radioactivity. He had been investigating how alpha particles were scattered when passed through thin metal foil. During the experiments, it seemed that some of these particles bounced back off the metal foil. Rutherford believed that this was the result of the encounter between the alpha particles and a large, concentrated positive charge. Hence, he suggested that the atoms were made up of a relatively large, positively charged core, the nucleus, surrounded by several relatively small orbiting electrons. However, in this model, the electrons should be radiating energy and losing momentum, and so atoms should not exist for very long. This problem was solved by Niels Bohr, who based his work directly on Rutherford's model. During 1913, Bohr suggested a model of atomic structure like Rutherford's, which he combined with Max Planck's concept of the quantum. According to Planck, changes in energy were not gradual but occurred in discrete packets, or quanta. According to Bohr's model, the electrons could occupy only particular levels of orbital energy. Thus, electrons were not radiating continuously but released their energy in distinct packets of energy with particular frequencies (Bowler and Morus 2005, pp. 258–259; Dear 2006, pp. 142–147). In this case, Bohr advanced the work done by Rutherford by working further on it, both theoretically and experimentally.

30.3.3 Geology

Alfred Wegener was the first to develop a theory to explain the apparent fit between the coastlines of Africa and South America. For Wegener, the older contraction mechanism proposed to explain mountain building through cooling was insufficient. In addition, it had been found that continents were not made by the same material as the ocean floors. Therefore, another mechanism should have been at work. Wegener thought that horizontal movements of the continents could provide an alternative explanation. In 1915, he proposed his theory of continental drift, in which he suggested that there once had been a single supercontinent, Pangaea, which very gradually drifted apart into recognizable continents. The evidence he used to support this theory was the significant similarities between the fossil records and geological formations on either side of an ocean, such as between the strata of Africa and Brazil. He also pointed out that his theory could explain the historical patterns of glaciation far away from the poles (Bowler and Morus 2005, pp. 238–242; Fara 2009, pp. 385–389). In this case, evidence was crucial in proposing a new explanation for observations. Although the apparent fit between the two continents made this explanation very plausible, additional evidence was required for it to become accepted.

30.3.4 Physics

At the beginning of the 1920s, it was widely accepted that the universe was dominated by the Milky Way Galaxy. Despite evidence to the contrary, Edwin Hubble managed to show that nebulae like the Andromeda Nebula (or Andromeda Galaxy) could not be part of the Milky Way Galaxy. Previous studies had identified a constant relationship between the period (the time between instances of highest luminosity) of a Cepheid variable (a class of star) and its luminosity. Hence, measurements of this period could be used to calculate its absolute luminosity, which—when compared with its apparent luminosity (how bright it appeared in the night sky)—could eventually be used to approximate its distance. This was possible because, when comparing different objects with the same absolute level of brightness, the less bright the object appears, the farther away it is. Hubble identified a Cepheid variable in the Andromeda Nebula and calculated its approximate distance, using the calculations of Henrietta Leavitt (almost a million light years; we now know that it is even farther away). The results suggested that it was too distant to be part of the Milky Way Galaxy. This gave rise to the “island universe” model (Bowler and Morus 2005, pp. 283–284; Fara 2009, pp. 390–391).

Watson and Crick obtained no evidence by themselves but based their conclusions exclusively on work done by others. The work of Bohr was not only based on, but also advanced in many ways, the work of Rutherford. Wegener advanced an idea that seemed obvious but worked for years to obtain supportive evidence, whereas Hubble advanced an idea that seemed contrary to the available evidence and soon managed to show that he was right. These examples demonstrate that there is no single, step-by-step method for doing science and that science is done in a unique and personal way.

30.4 Historical Illustrations to Show That Laws and Theories Are Distinct and Not Hierarchically Related Kinds of Scientific Knowledge

One common misconception about science is that theories gradually mature until they become laws, which suggests that laws are superior to the theories that preceded them. Laws and theories are related, but they are distinct kinds of scientific knowledge. Laws are generalizations or patterns in nature, whereas theories are explanations for why such laws operate in the way they do (McComas 2004). It is a common misconception that, with time and evidence, theories become laws. In truth, laws are generalizations and theories are explanations. One must be careful about this issue because occasionally even well-established ideas in science are mislabeled. A classic example is the notion of the "cell theory," an idea in every secondary school biology text that states that the cell is the smallest unit of structure and function, all living things contain cells, etc. It would be more accurate to call this the cell principle since it is a generalization, not an explanation. Students and teachers alike must recognize that the label associated with an idea, whether "law" or "theory," is not always indicative of its true philosophical nature.

30.4.1 Biology

Gregor Mendel is widely known for setting the foundations of genetics. Following the results of many breeding experiments, Mendel was ready by 1865 to present his conclusions, which we now know as "Mendel's laws." Almost every biology textbook presents the "law of segregation" and the "law of independent assortment" as examples of the conclusions that Mendel reached, although we now know that there are numerous exceptions. However, within limits, these laws permit accurate predictions. The distinction between laws and theories is particularly clear in this case, as Mendel was not able to provide a theory that would explain his observations and why his laws held. He talked about characters running through generations, but he had no idea of the gene as the explanation for his observations in inheritance. An interesting possibility is that Mendel was not actually trying to develop a theory of heredity. Rather, he focused on the study of hybridization in plants (Bowler and Morus 2005, pp. 196–198; Fara 2009, pp. 340–341). It should be noted that several theories of heredity were proposed during Mendel's life, all of which were developed in an evolutionary perspective, contrary to what Mendel was doing (Kampourakis 2013). Students should find it interesting that the idea that hereditary information was "delivered" in packets (i.e., genes) came before the discovery of genes themselves as actual entities and came long before the biochemical explanation that DNA was ultimately responsible for the hereditary code.

30.4.2 Chemistry

Dmitri Mendeleev is famous for coming up with the idea of the periodic law (although he was not the only one to do so), which led to the invention of the periodic table. Initially, he thought of arranging the elements, such as copper, silver, and gold, according to their chemical properties. Then he thought that it would also make sense to arrange the elements in the order of their atomic weights (which were possible to measure although the structure of atoms was unknown at the time). However, this way of arranging elements did not work well. Instead of changing his hypothesis, Mendeleev "changed" the data. He suggested that some atomic weights had been measured wrongly. He therefore slightly rearranged the order of the elements to make them fit in the pattern that he had conceived, so that elements with similar properties would lie underneath one another in the columns of the table. This left gaps in the table for other elements that were not yet discovered at that time, the properties of which were possible to predict. Such elements were discovered later and confirmed Mendeleev's predictions. Mendeleev's idea was entirely confirmed in the twentieth century when the atomic theory was developed, and it was shown that the properties of an element depended on its atomic number (the number of protons in its nucleus), whereas its atomic weight depended on the total number of protons and neutrons in its nucleus. The modern version of the periodic table ranks the elements in order of increasing atomic number, all elements in the same column having the same number of free electrons (Fara 2009, pp. 330–332). Mendeleev described a law that he could not explain in detail and which was later explained by the atomic theory.

30.4.3 Geology

Harry Hess proposed that ocean ridges were areas where molten rock welled up from the interior of the Earth. According to this "seafloor spreading" model, the hot mantle material spreads out, with the youngest rocks becoming solidified next to the ridges and the oldest rocks, laid down millions of years earlier, found farther away from the ridges. This model of seafloor spreading was strengthened by the observation of patterns of magnetism that had been revealed on the seabed, particularly through the existence of parallel stripes of normal and reversed magnetism alongside the mid-ocean ridges. As new rock welled up, it was imprinted by the current direction of the magnetic field of the Earth. When this field reversed, a new strip of reverse-magnetized rock would begin to form that would push the initial strip away from the ridge. This evidence, coupled with a comparison of fossils in West Africa and eastern South America, gave rise to the unifying explanation for all these phenomena—the theory of plate tectonics—proposed by Fred Vine and Drummond Matthews (Bowler and Morus 2005, pp. 247–249; Fara 2009, p. 388). In this case, the laws of physics formed the basis for supporting the theory of plate tectonics.

30.4.4 Physics

In 1687, Isaac Newton's work commonly known as the *Principia* was published, in which he proposed and established the inverse square law of gravity and the three laws of motion. He also established that the same kind of force was responsible both for maintaining the Moon in its orbit and for causing the acceleration of falling bodies at the surface of the Earth. However, although Newton had established the existence of these laws, he had no theory to explain why phenomena were taking place in the way described by them. For example, Christian Huygens accepted the existence of the inverse square law of gravity, but he thought that it was the task of natural philosophy to also explain it in mechanical terms. Newton knew that he was unable to do this and defended his work by saying that the demonstration of the existence of universal gravity to a near mathematical certainty was enough. For him, natural philosophy was a matter of establishing knowledge of natural effects, not necessarily of specifying the causes. Eventually, the fact that no one could properly understand Newton's gravitational forces was not an obstacle to their acceptance because they proved useful (Bowler and Morus 2005, pp. 46–48; Dear 2006, pp. 36–37). In this case, laws were established and were accepted although there was no theory available to explain them.

30.5 Using the History of Science to Show the Creative Aspect of Science

Scientific knowledge may often be presented as a set of facts and conclusions, but it involves a dynamic and exciting process that leads to such knowledge. Scientists apply creativity through their questions, methods for investigation, and inspirations that lead from evidence to conclusions. This is illustrated in the cases in which scientists were inspired by simple analogies to provide novel explanations for questions of interest.

30.5.1 Biology

In 1859, after considering a vast body of evidence for many years, Charles Darwin published his theory of evolution by natural selection. One crucial argument in support of natural selection came from an analogy between "natural" and "artificial" selection. The production of artificial varieties (such as fancy colors in pigeons) by breeders was a case in which major characteristics in animals were observed to change selectively from one generation to another. The study of animal breeding helped Darwin realize that the individual variation existing in animal populations could be used as raw material by breeders, who created new varieties using artificial selection. They selected individuals that happened to possess the traits of interest, allowing only those to breed while rejecting the others. Darwin thought that something similar might take place in nature. Through a process like artificial selection, natural selection, individuals that were better adapted might survive in a given environment, whereas individuals that were not well adapted might be eliminated

(Bowler and Morus 2005, pp. 146–147; Dear 2006, p. 97). As is obvious in this case, analogical thinking is a highly creative act. Animal breeding, both as a hobby and for economic purposes, was a popular endeavor in Britain at that time. Many people were involved in it, but only Darwin perceived the analogy between artificial selection and natural selection.

30.5.2 Chemistry

Antoine Lavoisier insisted on the importance of empirical, quantitative data for doing chemistry. He insisted that, as in physics, only experimental evidence could form a basis for the claims of chemists. Central in this new approach to chemistry was the creative development of a new chemical nomenclature in 1782, which Lavoisier and his colleagues claimed was based on direct experience and observation. According to this system, the simplest substances should be given simple names, whereas the chemical compounds should have more complex names to indicate the simpler ones from which they were formed. The main aim behind this nomenclature was to summarize the chemical experience of making or using the substance. For instance, sulfate of iron and sulfate of nickel were the compounds produced by the reaction of sulfuric acid with iron and nickel, respectively. Similarly, Lavoisier wanted to give simple names to substances that seemed to be simple. In this case, he relied on their properties and reactions. For instance, hydrogen got its name because its combustion produced water (Greek *hydor*), whereas oxygen got its name because its combustion with metals or carbon was thought to produce acids (Greek *oxy*). Lavoisier's highly creative act influenced chemistry after that time (Bowler and Morus 2005, pp. 67–71; Dear 2006, pp. 72–76).

30.5.3 Geology

As already mentioned, in 1915, Alfred Wegener suggested a theory of continental drift whereby continents moved away from or toward each other, giving rise to oceans or mountain ranges, respectively. To explain his model, he used an analogy with a newspaper torn into fragments. Wegener suggested that if the fragments could be reassembled so that the words on the paper could join up to make coherent sentences, it would be compelling evidence that the fit of the pieces was correct. Hence, in geological terms, if continents that were far apart seemed to fit each other when joined together—both in terms of shape and considering other evidence (e.g., paleontological)—as, for example, Africa and South America do, it would show that these continents are fragments of a larger continent (in this case, Pangaea) that underwent a breakup sometime in the past. Unfortunately, although Wegener had produced a model that was very intuitive and simple, he offered no underlying mechanism to explain how this might work and so was not accepted at the time (Bowler and Morus 2005, pp. 238–244; Fara 2009, pp. 385–389).

30.5.4 Physics

In 1824, Nicolas Sadi Carnot explained what happened in a steam engine as the result of the transfer of caloric (a fluid with which heat was associated) from one part of the engine to the other. Carnot suggested that what was important was the movement of caloric from a hot to a cold body, not its consumption as had previously been thought. The caloric that was developed in the furnace incorporated itself with the steam and was carried in the condenser that was above. There, the caloric was transferred from the steam to the cold water, which was thus heated. Hence, throughout the process, the steam was only a means of transporting the caloric. This idea was based on an analogy of the water movement in the water mills that Carnot's engineer father had studied. In a water-powered mill, water did work by falling from one level to a lower one. Hence, water was conserved while producing work. Carnot, in a creative leap, thought that in a similar manner caloric (which was then considered a fluid) did work in a heat engine by falling from one temperature to a lower one (Bowler and Morus 2005, pp. 82–83).

30.6 Using the History of Science to Demonstrate the Subjective Element of Science

Science, like all human activities, has a subjective component. Two scientists looking at the same data may interpret it differently because of their prior experiences and expectations. This does not make science less rigorous or useful, because the results must be discussed, debated, and confirmed within the wider scientific community to gain acceptance. However, quite often scientists are subjective in their decisions as they reach conclusions to confirm preconceived ideas.

30.6.1 Biology

Spontaneous generation, the idea that life could emerge from inanimate matter, was widely accepted in the eighteenth century. Georges-Louis Leclerc, Comte de Buffon, one of the most influential naturalists of his period, accepted spontaneous generation. In 1778, in his *Epochs of Nature*, he suggested two episodes of spontaneous generation during the Earth's history: one to produce the creatures living in the early, hot conditions of the Earth and the other to produce the ancestors of the modern forms. The issue of spontaneous generation was resolved less than a century later by Louis Pasteur, who became famous through a series of debates with the materialist physician Felix Pouchet. In a series of experiments, Pasteur showed that in all circumstances when the experimental apparatus was properly sterilized and contamination from the environment was prevented, no organisms appeared. What was initially seen as spontaneous generation was in fact the result of the contamination of the experimental apparatus by microorganisms coming from outside. However, Pasteur's motivations were not solely scientific. He was a conservative Catholic who aimed to counter the arguments of the radical materialist Pouchet. In a sense, Pasteur did not aim to discover what was going on but, rather, to confirm a conclusion he had already arrived at subjectively and for nonscientific reasons. Ironically, it was eventually concluded that both were right, given that boiling kills more microorganisms but also that some can nevertheless survive forming spores (Bowler and Morus 2005, pp. 135–136, 447–448; Fara 2009, pp. 305–306).

30.6.2 Chemistry

Jan Baptist van Helmont thought that water was the only element in nature, contrary to the prevailing view that everything was composed of one or more of four elements (air, earth, fire, water). Van Helmont is famous for an experiment that nowadays would be considered as providing evidence for photosynthesis. In 1649, he planted a willow tree in 200 pounds of dried soil and regularly nourished it with distilled rainwater. During the course of five years, the tree grew in weight from 5 to 169 pounds, while the weight of the soil remained the same. However, from this experiment, van Helmont concluded that the increase in size and weight of the tree had been exclusively due to the water added. Van Helmont performed this experiment to support his claim that water was the only element in nature and did not consider any other explanation for what he observed (Bowler and Morus 2005, p. 59).

30.6.3 Geology

James Hutton and Charles Lyell are considered the founders of uniformitarianism, the view that considered the Earth's history as a cycle of slow, gradual changes and that ruled out any appeal to unknown causes. Hutton had been the first to insist, in 1795, that the processes responsible for forming the rocks had all occurred at the same rate as could be observed in his day. According to him, there was a perfect cycle at work in which the elevation of new land exactly balanced the destruction of the old land by erosion. However, Hutton's theory did not attract much attention. The uniformitarian model was revived in 1830–1833 by Lyell, who provided evidence of just how much change was actually occurring through the action of volcanoes, earthquakes, and erosion. He eventually rejected catastrophism as an explanation for the changes that the Earth had undergone and suggested that a long sequence of ordinary changes could have produced the observed effects, given enough time. It is interesting that both Hutton's and Lyell's motivation for setting up such a theory was their own religious beliefs. Both were deists who believed that a benevolent and wise God had designed a machine that could work forever without His involvement (Bowler and Morus 2005, pp. 120–122; Fara 2009, pp. 268–271).

30.6.4 Physics

Like most of his seventeenth-century contemporaries, Johannes Kepler was a Platonist and thought that the universe operated according to harmonic principles. Although he accepted Copernicus's idea that there were six planets including Earth, he was puzzled over why this *had* to be the case. To answer this question, Kepler thought that the number of planets might be related to the number of solid figures that could be constructed using Euclidean geometry (octahedron, icosahedron, dodecahedron, tetrahedron, and cube). He thought that if he nested these figures one inside the other—so that, in each case, the corners of the inner figure just touched the surface of the sphere surrounding the solid, and this sphere, in turn, just touched the inner sides of the surface of the next solid—he could define six spheres, one for the orbit of each planet. In this model, there was a magnetic soul—the Sun—that attracted and repelled the planets to control their paths. This idea was based on a mystical belief that the heavens must be governed by geometry. However, he later rejected this idea as he came to realize that the shape of the orbits of the planets was elliptical. Kepler thought that an imaginary line, joining the Sun to a planet moving in orbit around it, swept out equal areas at equal times. After this discovery, and after trying several possibilities, he realized that each planet moved in its own elliptic orbit, rather than conforming to a specific geometric expectation (Bowler and Morus 2005, pp. 32–33; Fara 2009, pp. 135–137). Kepler had a Platonic view of the universe and was convinced that it should be true. Yet, he later rejected this subjective view in the light of empirical data.

30.7 Using the History of Science to Illustrate the Historical, Cultural, Political, and Social Influences on Science

Science is an enterprise that lies within society and, as such, both reacts to and is somewhat governed by societal norms and needs. The kind of research performed is best understood by considering factors such as history, religion, culture, and social priorities. The expense usually associated with scientific research, as well as the impact that its conclusions may have on society, make science a process that cannot be properly understood outside its context. Doing science not only involves having novel ideas or clever insights but also depends on factors that have to do with the personality of the scientist and the societal context in which the work is done. Also, it is important to understand that the lack of culture and gender diversity throughout much of the history of science is not to be defended but can be understood in terms of society itself. Science now is much more inclusive even if there is still much more to be done in that regard.

30.7.1 Biology

Charles Darwin had been considering the possibility of evolutionary change as early as 1839, but he hesitated to publish his ideas because he wanted to accumulate as much evidence as possible in support of them and because he was also concerned about the reaction of people with strong religious views (his own wife included), as they might consider his theory an insult to the established beliefs of the time. In 1844, a book titled *Vestiges of the Natural History of Creation*, anonymously published by Robert Chambers, caused an enormous public reaction, being the first book to instigate a widespread discussion of evolutionary issues. This reaction made Darwin concerned, and he realized that if he published his work, it would be compared to the (largely speculative) theory presented in the *Vestiges*. Therefore, it was crucial for Darwin to establish his theory on solid grounds and to let the instability subside. So, in 1844, Darwin wrote a sketch of his theory and shared his views with Joseph Dalton Hooker in a letter that he wrote in the same year. Darwin later changed his mind and gradually started working on a big treatise that he intended to call *Natural Selection*. However, a letter of June 1858 from Alfred Russel Wallace, who discussed the mechanism of evolution in ways that looked like Darwin's, forced Darwin's decision to publish his views. He immediately started writing an extended version (what he called an "abstract") of his theory that was ultimately published in November of 1859 as the *Origin of Species* (Bowler and Morus 2005, pp. 147–149; Fara 2009, pp. 277–280). It should be noted that Darwin's theory was not complete before 1857, and there were several differences between the version in the *Origin* and earlier conceptualizations. Darwin was diligently accumulating evidence in support of his theory for years, but social factors played a crucial role both in his hesitance to publish his ideas and, finally, in encouraging him to proceed to publication.

30.7.2 Chemistry

The importance of social status in the pursuit of science is illustrated by the case of Antoine Lavoisier discussed earlier with reference to another Key NOS element. The independently wealthy Lavoisier had established a reputation as a chemist by performing a series of experiments on the nature of the air. In 1775, he was appointed as commissioner to run the gunpowder industry, and he set up his laboratory in the Paris Arsenal. Based on his work there, he established the superiority of the model of combustion to the phlogiston theory and gave oxygen its name. It was also there that he carried out experiments on respiration, in collaboration with Pierre Laplace, and concluded that animals maintained their body temperature by the conversion of oxygen into "fixed air" (an old name for carbon dioxide), in the same way that charcoal gave off heat when it burned. In parallel with all this activity, Lavoisier was a tax collector and lawyer. Because of his financial dealings, after the French Revolution he was considered a wealthy landowner who exploited the poor, and so he was executed in the guillotine. Thus, the career and the life of an influential chemist was terminated for political reasons (Bowler and Morus 2005, pp. 67–71; Fara 2009, pp. 209–213). Students will find it interesting to examine Lavoisier's life beyond science and perhaps speculate what he might still have contributed to science had he not be executed during the French Revolution. As fellow scientist Joseph-Louis Lagrange said, "It took them only an instant to cut off this head, and one hundred years might not suffice to reproduce its like."

30.7.3 Geology

Although Alfred Wegener, as we already described, suggested the theory of continental drift as early as 1915, it was not given much attention until the early 1960s. His critics rejected Wegener's theory because it had implications that contradicted much of the available evidence, which in turn seemed to support other types of explanations. However, this was not the only reason for the criticisms. They also arose from the fact that Wegener was an outsider to the community of professional geologists and was considered not to have paid his debts in the field. Wegener was a geophysicist and meteorologist, and he was likely seen as trying to enter a territory claimed by others. His proposal was widely rejected and, in some cases, even ridiculed; he was depicted as an uncritical enthusiast who had surveyed the literature to find support for his claims and ignored several arguments to the contrary (Bowler and Morus 2005, p. 244).

30.7.4 Physics

The importance of social factors, especially of patronage, to the practice of science is clearly seen in the case of Galileo, Brahe, and Kepler. By 1609, Galileo Galilei had discovered four new planets through his newly improved telescope. He named the planets *Medicean Stars* and dedicated his book to the Grand Duke Cosimo de Medici of Tuscany to attract his patronage. Galileo's reward was a major change in status: he was made professor of philosophy at the University of Pisa and was appointed court philosopher and mathematician to Cosimo. Tycho Brahe was the son of an influential member of the Danish court. Hence, he was not only in the position to finance his career in astronomy but also received support from the Danish crown. Moreover, Brahe worked for Emperor Rudolph starting in 1599. Following his death in 1601, Johannes Kepler succeeded Brahe as Rudolph's mathematician and inherited his astronomical instruments and the even more precious observational records. Kepler named his set of planetary calculations the *Rudolphine Tables* to honor his patron (Bowler and Morus 2005, pp. 29–32; Fara 2009, pp. 132–138). These examples highlight the importance of aristocratic and royal patronage for sustaining astronomical work.

30.8 Science, Engineering, and Technology Influence Each Other But Are Not the Same

The questions investigated by science are either related to practical needs or aim at a fundamental understanding of nature. We now usually distinguish between science, engineering, and technology and describe the ways in which they affect each other. There are cases in which scientific advancements improved technology, but what is even more interesting is how technological advancements supported the advancement of science. The key issue of concern is that students see both the relationship and the distinctions between technology, engineering, and science and recognize the discrete roles played by each. It would be unfortunate, for instance, if students were to confuse as too similar the basic knowledge-seeking rationale of science with the application and problem-solving rationales that guide engineering and technology. The goals and rationales of science are simply not the same as those for engineering and technology.

30.8.1 Biology

Robert Hooke was one of the early microscopists and the one who coined the term "cell." In 1665, he published *Micrographia*, the first substantial book on microscopy that brought the small-scale world into attention. However, the nature and function of cells remained a mystery until the nineteenth century, when improved microscopes allowed a more fine-grained analysis of the structure of tissues. This led to the cell concept, that tissues were made up by cells, proposed by Matthias Jakob Schleiden in 1838 for plants and extended a year later by Theodor Schwann to animals. In his *Microscopical Researches*, published in 1847, Schwann provided microscopic studies of cells and their nuclei and showed that every tissue, animal, and plant was composed of cells. From these observations, he argued that the cell was the basic unit of life. In 1855, Robert Remak showed that cells were formed by a process of division initiated in the nucleus. In 1858, Rudolph Virchow provided the final element to the cell concept: that the cell is the basic unit of life and that each new cell is formed only by the division of preexisting cells (Bowler and Morus 2005, pp. 172–173; Fara 2009, pp. 160–161). The detailed study of cells was therefore highly dependent on the technological advancement of microscopes.

30.8.2 Chemistry

Johann Becher performed chemical investigations into the origins of minerals with the hope of finding new ways of exploiting relevant resources for economic gain. In his *Physica Subterranea* (1667), he suggested that minerals were made up of three types of earth: mercurous earth, fatty earth, and vitreous earth. When a substance was burned, he supposed that the fatty earth was liberated, a conception that formed the basis of Stahl's phlogiston theory. Becher's ideas and experiments on the nature of minerals and other substances were also published in his *Physica Subterranea*. His research into the theory of mineral production was an effort to improve mining technology for the benefit of the state. Through his attempt to improve a specific technology and to better understand the origins of minerals, a better understanding of the natural world also emerged (Bowler and Morus 2005, pp. 60–61).

30.8.3 Geology

During World War II, Patrick Blackett helped produce an extremely sensitive magnetometer for the detection of magnetic mines. He later used this device to trace minute magnetic fields locked into the rocks of the crust of the Earth. It was assumed that these fields had been imprinted onto the rocks when they were formed, and so by measuring them one could produce a record of the Earth's magnetic field through geological time. As soon as details of the remnant magnetism (paleomagnetism) from rocks in different areas were compared, it was made clear that they were not aligned with the current state of the Earth's field or with each other. This meant either that the rocks had moved since their formation or that the magnetic poles of the Earth had shifted. The most likely explanation was that the continents had moved from the position they had occupied in earlier geological periods, given that the remnant magnetic fields were different in rocks coming from different parts of the world (Bowler and Morus 2005, pp. 246–247). In this case, a technology developed for war purposes eventually provided evidence for one of the most important developments in modern geology.

30.8.4 Physics

Fearing that the Nazis were working on an atomic bomb, the British made the first moves toward its design. By 1939, it had become clear that the only way to derive significant amounts of energy from the breakup (fission) of radioactive atoms was by starting a chain reaction. Some radioactive elements, such as uranium-235 and the artificial element plutonium, liberated neutrons that, in a quantity that exceeded a critical mass, could produce a chain reaction. If this were done without control, a vast amount of energy would be liberated in the form of an explosion. The central problem was what that critical mass should be. In 1940, two German scientists, Otto Frisch and Rudolf Peierls, who had been working in England, calculated that the critical mass should be about 5 kg. However, there was, yet, no way of extracting this amount of fissionable material from natural sources. Hence, a way of extracting uranium-235 in quantity was required. However, it was suggested that given the threat of German invasion in England, the actual production should be done in the United States. The US administration's key scientific advisers, Vannevar Bush and James B. Conant, were convinced that the program was likely to be successful, so President Roosevelt approved funds for research. In 1942, Enrico Fermi, who during World War II escaped from Italy to work in the United States, soon built a reactor and initiated a controlled chain reaction. One function of the reactor was to convert uranium-238 into plutonium, another potential fissionable material for a bomb. Research went ahead with the aim of making bombs with both uranium-235 and plutonium, at the start of what became known as the Manhattan Project. Meanwhile, Robert Oppenheimer began the design of the bomb. As technical problems emerged, a closer cooperation between the theoretical physicists and the engineers was required. Hence, in a sense, the Manhattan Project was changing the way in which science was done, requiring scientists to engage in close cooperation with military and industrial engineers (Bowler and Morus 2005, pp. 471–479; Fara 2009, pp. 370–374) in work that was complementary but not the same, either in practice or in underlying philosophy. It is important that students understand this distinction.

30.9 Scientific Knowledge Is Tentative But Durable and Self-Correcting

The logical and careful knowledge-generation process of science is an effective way to study the natural world, and the scientific conclusions formed in this fashion are usually long-lasting and useful. One of the hallmarks of science, however, is its ability to remove incorrect ideas in favor of ones that are more accurate and, thus, even more useful.

30.9.1 Biology

Jean Lamarck was a French naturalist who made important contributions to invertebrate taxonomy and proposed the first theory of evolution in 1809. He believed that a process of progressive adaptive evolution was at work and that organisms were always changing into something else. Georges Cuvier ridiculed Lamarck's evolutionary theory, arguing that the structure of each species was so carefully balanced that transitional forms would not be able to survive. However, it was Cuvier's anatomical work and study of fossils that eventually provided evidence for evolution.

Cuvier focused on the internal structure of organisms and showed that seemingly very different organisms shared crucial similarities. He also showed that extant organisms were like extinct ones found in the form of fossils, as, e.g., he demonstrated that mastodons and mammoths were similar to but distinct from modern elephants. Finally, he also showed that the older a rock was, the more unfamiliar were the fossil organisms found in it. Eventually, proponents of evolution, including Charles Darwin, relied a lot on Cuvier's conclusions to support the idea that species have evolved through time (Bowler and Morus 2005, pp. 136–138; Fara 2009, pp. 275–277). The data that were initially thought to question the idea of evolution eventually came to its support.

Another wonderful example of this NOS aspect is found in the story of a misidentified fossil tooth, as told by Stephen Jay Gould (1991) and by paleontologist Donald Prothero (2007). In 1917, an odd-looking and fragmentary tooth discovered in a rich Miocene bone bed in western Nebraska was sent to Henry Fairfield Osborn at the American Museum of Natural History in New York, who somewhat quickly suggested that it might be the tooth of an anthropoid ape. This was not as bizarre an idea as one might think, given Osborn's prediction that ape-like ancestral humans might have migrated from Asia with Miocene-age animals. Despite doubts, he published the specimen as *Hesperopithecus haroldcookii* in 1922. The tabloid *Illustrated London News* picked up the story and even published a reconstruction of an ape-man who had presumably lost the tooth millions of years earlier. The story of "Nebraska Man" was born and passed quickly from science into the popular sphere. The reason that we no longer talk about Nebraska as a site of human origins is that after study of additional fossils, the tooth was soon found to be that of a peccary, a pig-like animal. Although at many levels peccary and human teeth are quite similar, a mistake is still a mistake. A paper correcting the error was published by Osborn colleague William King Gregory in 1927, and the tooth was quickly forgotten by those interested in human origins. Unfortunately, creationists got involved and trumpeted the error as a major faux pas on the part of scientists, evidence—for them—that science can't be trusted and that there are no valid human fossils. Sadly, and frustratingly, creationists never use this story to demonstrate that, although scientists do make mistakes, science itself will correct those errors. The Nebraska Ape is a wonderful story of the self-correcting nature of science and provides clear evidence that scientific ideas that survive the test of time are worth accepting.

30.9.2 Chemistry

Georg Stahl developed his theory of phlogiston in the early eighteenth century to explain why certain metallurgical processes work. According to this theory, pure metals were the result of the combination of metal ores with phlogiston during the heating process. Phlogiston was a hypothetical substance that was supposed to leave a burning object. By about 1770, Lavoisier was convinced that the air must also play a role in this reaction. In 1772, based on his experiments, he suggested that heating metal in air led to the production of a calx (a combination of metal and gaseous material) and liberated phlogiston in the form of heat. Based on his experiments, Lavoisier hypothesized that the main process during combustion was the combination of the burning substance (e.g., metal) with aerial matter, which was why the substances increased in weight. By the same year, Carl Scheele suggested that air was a mixture of two substances, one that prevented burning and one that promoted combustion. In 1774, Joseph Priestley found that when red calx of mercury was heated, an air that seemed to contain little or no phlogiston at all was produced. This was termed "dephlogisticated air" because it contained little or no phlogiston. By 1775, Lavoisier refined Priestley's account and argued that it was dephlogisticated air (which he called "oxygen") that played the key role in combustion. In introducing oxygen, Lavoisier led to the abandonment of the phlogiston theory (Bowler and Morus 2005, pp. 63–64, 67–69; Dear 2006, pp. 77–78). The replacement of the phlogiston theory by the oxygen theory is another example of the tentative and self-correcting aspect of scientific knowledge.

30.9.3 Geology

During the late eighteenth century, Abraham Werner promoted the "Neptunist" idea that land was exposed because a vast ocean that once covered it had gradually diminished in depth. Werner assumed that as the ocean dried up, the chemicals in it were dropped out in sequence and each type of rock was laid down in a period in Earth's history. As a result, erosion of the land surface would add a regular sequence of sedimentary rocks. Neptunism was widely accepted, and some scientists even tried to link it with Noah's flood. However, this theory was refuted by evidence that the same types of rocks could be laid down at different periods, and by the early nineteenth century it could no longer be sustained. Alexander von Humboldt viewed the power of volcanoes and earth movements when he studied the Andes Mountains; he and many others abandoned Neptunism and suggested that earth movements explained how the sedimentary rocks were elevated to form land (Bowler and Morus 2005, pp. 111–112).

30.9.4 Physics

In 1883, Heinrich Hertz performed experiments on cathode rays to determine whether they carry an electric charge. In one experiment, he separated cathode rays from ordinary electricity produced in a cathode tube and caused the cathode rays to enter an electrometer, but no electric charge was identified. In a second experiment, he introduced oppositely electrified plates into the tube to see whether the cathode rays were deflected electrically, but no deflection was produced. Hertz concluded that cathode rays carry no electric charge and, hence, are not composed of charged particles. A few years later, Joseph John Thomson showed that Hertz was wrong to assume that the air in the cathode tube was sufficiently evacuated to allow electrical effects to occur. Thomson concluded that the rays are indeed composed of electrically charged particles (later called "electrons"). He also experimentally measured their ratio of mass to electric charge by deflecting the cathode rays in a magnetic field and, later, in an electrostatic field. For his experiments with cathode rays, Thomson is credited with the discovery of the electron (Bowler and Morus 2005, pp. 254–257; Fara 2009, p. 324; see also Achinstein 2008).

30.10 Science Cannot Answer All Questions

This is a complicated issue with respect to the nature of science. This NOS idea may seem to include the questions that *science has not answered yet* (but may answer in the future), but it includes those that *science cannot answer* (because they fall outside its realm). There are questions that science cannot answer because no relevant evidence could be found or because the methods of science are simply not applicable. For instance, science cannot answer questions concerning the value of art (which painting is better than another?), morality (what is the correct moral choice?), or faith (which religion is most valid?). Spiritual issues are often among the most interest to students, but we should not neglect others example such as the application of scientific principles to the development of weapons of mass destruction and the ethical issues surrounding stem cell research.

30.10.1 Biology

In 1848, Richard Owen proposed a basic pattern for all vertebrate animals, known as the *vertebrate archetype*. This was an idealized model of the simplest conceivable vertebrate, of which all real vertebrate species were adapted modifications. In this sense, primitive fish possessed the simplest modifications and humans the most. This offered a better form of the argument from design (the idea that organisms were artifacts designed by a wise and benevolent Creator), because it implied that such an underlying archetypal pattern could only have arisen in the mind of the Creator. It is interesting that Owen went so far as to define the concept of homology—the idea that the same combination of bones could be modified in different species adapted to different environments. However, despite this and the fact that he saw the successive expressions of the archetype as a progressive pattern unfolding through time, he did not consider the possibility of evolution and he insisted that each species was a distinct unit in the divine plan. It was Darwin who, drawing on a similar developmental model, elaborated his theory of branching evolution (Bowler and Morus 2005, p. 139). Whether such a plan exists and what exactly God had in mind when he conceived it are questions that cannot be answered by science.

30.10.2 Chemistry

Joseph Priestley is famous for his "discovery" of dephlogisticated air (later called "oxygen" by Lavoisier) in 1774. Priestley believed that everything in nature had a role to play to maintain its economy. He believed that different "airs" played particular roles in the natural order. He regarded this as a proof of divine benevolence, a natural mechanism through which God kept the world in a state of equilibrium. But for a political and religious radical like him, this view of nature's economy had important political and social consequences. He thought that scientific instruments could help reveal the proper order of nature, on which the social order should then be based. But since there was something wrong with the prevailing social order, scientific instruments could also be used as political instruments to show how social injustices were at odds with nature (Bowler and Morus 2005, p. 64). In other words, by using scientific processes, Priestley wanted to provide answers and solutions to social issues; but these fall outside the realm of the study of nature.

30.10.3 Geology

In 1812, Georges Cuvier published his study of fossil vertebrates, along with suggestive evidence for catastrophic earth movements and tidal waves. William Buckland, one of his followers in England, suggested that geology could provide evidence that Noah's flood had taken place. In 1823, he described a cave in the hills of Yorkshire that had been filled with mud, in which the bones of hyenas and their prey were buried. A universal flood was the only explanation for the fact that a cave in the hills had been filled in this way. In addition, this event seemed to have been accompanied by a climatic transformation, since no hyenas could be found in Europe. For Buckland, this was evidence of a catastrophic event that could fit in with the events described in the book of *Genesis* (Bowler and Morus 2005, p. 116). But *Genesis* is not a scientific text; like any religious text, it may inform one's spiritual life but should not be read literally.

30.10.4 Physics

James Joule was interested in finding ways of quantifying the relationship between heat and work. The conclusion of his paddle-wheel experiments was that heat was literally turned into motive force in the process of producing work. For him, these experiments carried not only a scientific but also a theological message. He was convinced that his experiments were proof of the conversion of one force to another and of the conservation of force in general. In 1847, at a public lecture, he argued that conservation and conversion processes existed in nature. This was an explicitly theological argument, because what he claimed was that since God had created force and matter, neither of them could be lost or destroyed. Any apparent loss of force was simply the result of conversion of one kind of force to another, as happened in the paddle-wheel experiment with the transformation of work to heat (Bowler and Morus 2005, pp. 88–89). But although understanding whether energy is converted from one kind to another or is just lost is a scientific question, whether this reveals a divine plan is not a question that science can answer or even address.

30.11 Conclusions

NOS is an essential element of science instruction. However, many teachers find it difficult to couple NOS with traditional content for instructional purposes. We have based this chapter on an understanding that it is most likely that science teachers will be able to engage students in conversation about NOS only by interweaving such conversations with the standard content of the science curriculum. Therefore, we have endeavored to locate a variety of historical examples illustrating each major NOS idea for each of the major science disciplines (biology, chemistry, geology, and physics). We hope to encourage science teachers to blend the foundational knowledge provided by NOS with the expected science content and to do so explicitly and in context as recommended by decades of science education research. When teachers have a rich understanding of how the history of science can be leveraged to teach both historical and philosophical lessons, it will be possible to teach the expected science content while teaching about how science works.

Of course, the historical cases selected are not the only or the most appropriate ones to illustrate important NOS concepts. In fact, we would challenge our readers to add as many valid examples as possible from the history of science to enliven their teaching of the nature of science. But we wish to point out that because Mendel, Darwin, Newton, Joule, Lavoisier, Mendeleev, Wegener, Lyell, and many others are often mentioned in science textbooks, the rationale for discussing these key scientists should be clear (for the case of Mendel, see Campanile et al. 2015). Yet even their stories are rarely used explicitly to discuss NOS aspects. Our core argument is that even when drawing on only those historical figures mentioned in textbooks (see McComas 2008a, b), teachers should take the opportunity to use related stories to teach about NOS. We have provided here both a framework for the inclusion of NOS in science teaching and a collection of historical episodes that might prove useful for this purpose. Our hope is that we have encouraged science teachers to make these important connections with students and bring NOS and the history of science together in the classroom.

Acknowledgments Please note, this chapter has been adapted from one originally appearing as McComas, W.F. and Kampourakis, K. (2015), “Using the history of biology, chemistry, geology, and physics to teach aspects of the nature of science.” Review of Science, Mathematics, and ICT (Information and Communication Technology) Education, 9(1) 47–76. Permission to reprint has kindly been granted by editor Konstantinos Ravanis.

References

Abd-El-Khalick, F., & Lederman, N. G. (2000). The influence of history of science courses on students' views of nature of science. *Journal of Research in Science Teaching, 37*(10), 1057–1095.

Achinstein, P. (2008). Evidence. In S. Psillos & M. Curd (Eds.), *The Routledge companion to philosophy of science* (pp. 338–348). New York: Routledge.

Bowler, P. J., & Morus, I. R. (2005). *Making modern science: A historical survey*. Chicago: University of Chicago Press.

Campanile, M. F., Lederman, N. G., & Kampourakis, K. (2015). Mendelian genetics as a platform for teaching about Nature of Science and Scientific Inquiry: The value of textbooks. *Science & Education, 24*, 205–225.

Dear, P. (2006). *The intelligibility of nature: How science makes sense of the world*. Chicago: University of Chicago Press.

Fara, P. (2009). *Science: A four thousand year history*. Oxford: Oxford University Press.

Gould, S. J. (1991). An essay on a pig roast. In *Bully for brontosaurus* (pp. 432–447). New York: Norton.

Kampourakis, K. (2013). Mendel and the path to genetics: Portraying science as a social process. *Science & Education, 22*, 293–324.

McComas, W. F. (2004). Keys to teaching the nature of science: Focusing on the nature of science in the science classroom. *The Science Teacher, 71*(9), 24–27.

McComas, W. F. (2008a). Proposals for core Nature of Science content in popular books on the history and philosophy of science: Lessons for science education. In Y. J. Lee & A. L. Tan (Eds.), *Science education at the nexus of theory and practice*. Sense: Rotterdam.

McComas, W. F. (2008b). Seeking historical examples to illustrate key aspects of the nature of science. *Science & Education, 17*, 249–263.

Prothero, D. R. (2007). *Evolution: What the fossils say and why it matters*. New York: Columbia University Press.

Chapter 31
Using the Pendulum to Teach Aspects of the History and Nature of Science

Michael R. Matthews

Historically and philosophically informed teaching about the pendulum can convey important lessons about the nature of science:

- The interplay of mathematics, observation, and experiment in the development of modern science
- The interdependence of philosophy and science.
- The ambiguous role of empirical evidence in the confirmation or falsification of scientific claims.
- The contrast between modern scientific conceptualizations and those of common sense.

The Scientific Revolution is arguably the most significant episode in human history. Its scientific, philosophical, social and cultural impact, initially on Europe, and subsequently on the rest of the world, has been without parallel (Cohen 1985; Lindberg and Westman 1990; Wootton 2015). The core of the scientific revolution occurred in the half-century between the publication of Galileo's *Dialogue Concerning the Two Chief World Systems* (1633) and Newton's *Principia* (1687). In this 50-year period, Newton brought to fruition what Galileo had begun: A mathematical and experimental way of investigating nature displaced the varied common-sense, observational, philosophical, and tradition-bound ways that had hitherto dominated attempts to understand the world.

The new experimental and mathematical science, frequently in conjunction with colonial and commercial interests, spread rapidly from its origins in western Europe to the far reaches of the globe (Pyenson 1993). The science of seventeenth-century western Europe, initially known as 'the new science', became Western science, or

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_31

'universal science', or 'modern science'. The common pendulum – a swinging weight suspended by a string – played an enormous and overlooked role in the creation and spread of this new science. In emulation of the new science, new ways of understanding history, law, ethics, economics, religion, politics, and most cultural institutions came into being. This application of the new scientific methods to social, cultural and religious issues has been called 'The Enlightenment'. It was the eighteenth-century fruit of the seventeenth-century pendulum-enabled, natural-philosophy seed. The Enlightenment was an historical movement that formed and continues to shape the modern world (Dupré 2004; Pagden 2013; Postman 1999).

This chapter will show how teaching pendulum motion can be used to illustrate many important features of science, commonly labelled 'nature of science' (Matthews 2012), that school students should understand, and that are increasingly being demanded by natural and provincial curricula (Hodson 2014; McComas 2014; Olson 2018). These are:

- The centrality of experiment in the creation and pursuit of modern science.
- The indispensable role of mathematics in science.
- The impact of science on culture and society and the reverse influence of society and culture on science.
- The ambiguous role of empirical evidence in the confirmation and falsification of scientific claims.
- The contrast between the inherently idealised and abstracted conceptualisations of modern science and the conceptualisations of nature given in common sense.
- The role of philosophy, politics and values in the development of science.

Unfortunately, the centrality and importance of the pendulum for the development of modern science is often not reflected in textbooks or school curricula. The topic is near universal; but it is stripped of its rich philosophical and historical dimensions. The mythical story of Galileo and the church chandelier might be told, the 'Galilean laws of pendulum motion' might be demonstrated or discovered in laboratory classes, or perhaps the pendulum might be used as an example of more general simple harmonic motion. Not only is the pendulum's rich history ignored, but rich opportunities to learn about the nature of science are also passed over (Matthews 1998, 2014).

31.1 The Pendulum and the Foundation of Modern Science

The pendulum was central to the studies of Galileo, Huygens, Newton, Hooke and all the leading 'revolutionary' natural philosophers of the seventeenth century. Teaching about the pendulum in science classes can be a way of introducing students to this momentous historical episode and also allows them to see how the pendulum continued to play a central role in the development of eighteenth- and nineteenth-century physics, indeed right up to the present time where coupled 'chaotic' pendulums contribute to the 'testing' of chaos theory (Baker and Blackburn 2005).

In the seventeenth and eighteenth centuries, experiments with the pendulum, and development of associated mechanical theory, led to many significant findings that shaped modern science and modern society, such as:

- Enabling an accurate method of timekeeping that had great social consequences and that led to solving the longitude problem and facilitating trade, exploration, and colonisation.
- Providing the first universal and natural *standard of length*.
- Allowing formulation of the conservation of energy and momentum laws.
- Determining the value of the acceleration due to gravity **g** and consequently solving numerous dynamical and mechanical problems.
- Showing the variation of **g** from equatorial to polar regions and hence establishing the oblate *shape of the earth*; this was some three centuries before satellite pictures could make the earth's shape visually apparent.
- Providing crucial evidence for Newton's synthesis of terrestrial and celestial mechanics whereby he showed that fundamental laws are universal in the solar system, not peculiar to our earth.
- Showing the equivalence of inertial and gravitational mass.
- In the nineteenth century, with Léon Foucault's dramatic demonstrations in Paris, providing a dynamical proof for the rotation of the earth on its axis, something believed since Copernicus, and required by his theory, but never effectively proved.
- Providing an accurate measure of the density and hence mass of the earth and much more.

Physicists, historians and philosophers have long recognised the great debt modern science and society owes to the pendulum (Baker and Blackburn 2005; Matthews 2000; Matthews et al. 2005). The historian Bertrand Hall attested:

> In the history of physics, the pendulum plays a role of singular importance. From the early years of the seventeenth century, when Galileo announced his formulation of the laws governing pendular motion, to the early years of this century, when it was displaced by devices of superior accuracy, the pendulum was either an object of study or a means to study questions in astronomy, gravitation and mechanics. (Hall 1978, p. 441)

The physicists Gregory Baker and James Blackburn, in their recent book *The Pendulum: A Case Study in Physics*, say:

> The pendulum is not just a device of pure physics; it is fascinating because of its intriguing history and the range of its technical applications spanning many fields and several centuries. Thus, we encounter, in this book, Galileo, Cavendish, Coulomb, Foucault, Kamerlingh Onnes, Josephson, and others. (Baker and Blackburn 2005, p.v)

The full range of topics and disciplines – historical, philosophical, scientific, pedagogical, psychological, astronomical – to which the pendulum has contributed are laid out in the 30-chapter book *The Pendulum: Scientific, Historical, Philosophical and Educational Perspectives* (Matthews et al. 2005) which includes 12 chapters dealing with pedagogical approaches from preschool to graduate classes. One core aspect of NOS that the pendulum illustrates for students is that:

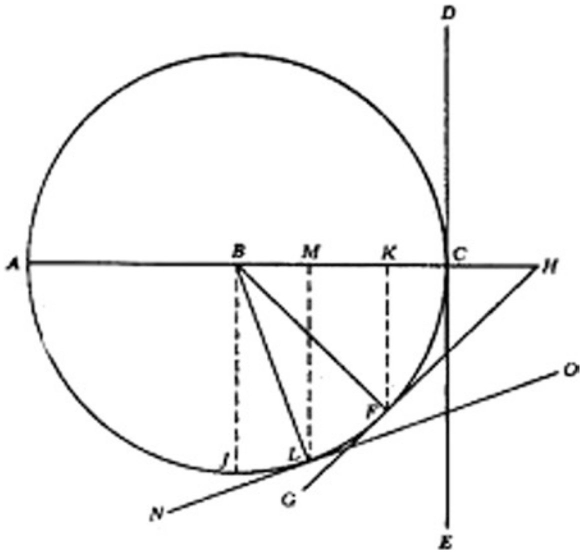
 # Science has a tradition, it is dependent upon its past, it builds on what is established, being scientific involves engagement with this tradition, it is a social and historical activity.

31.2 Galileo and the Pendulum

The modern science of the pendulum began with Galileo. In a letter of 1632, Galileo surveyed his achievements in physics and recorded his debt to the pendulum for enabling him to measure the time of free-fall, which, he said, "we shall obtain from the marvelous property of the pendulum, which is that it makes all its vibrations, large or small, in equal times" (Drake 1978, p. 399). After his appointment to a lectureship in mathematics at the University of Pisa in 1588, Galileo quickly became immersed in the mathematics and mechanics of the 'Superhuman Archimedes', whom he never mentions 'without a feeling of awe' (Galileo 1590/1960, p. 67). Archimedes was perhaps the most famous ancient to utilize mathematics in the formulation and solving of mechanical problems. Galileo's immersion in Archimedean texts and mechanical problems led to his early work titled *On Motion* (1590/1960) in which he deals with the full range of mechanical and physical problems then being discussed among natural philosophers.

In the work, he constructed the diagram (Fig. 31.1) depicting a combination of different motions: free-fall (DE), motion on balances (AC), motion on inclined

Fig. 31.1 Many motions in one figure



planes (HFG) and circular motion (CFLJ). In this discussion, the physical circumstances are depicted geometrically, and mathematical reasoning is used to establish various conclusions in physics: Galileo here begins the thorough mathematising of physics which is entirely modern. Galileo's genius was to see that all the above motions could be dealt within one geometrical construction, and this will also represent a pendulum suspended at B whose length is the radius of the circle. At any point on the circumference, the bob can be understood as moving on an inclined plane tangential to that point. That is, motions which appeared so different in the world could all be depicted and dealt with mathematically in a common manner. This will be a recurrent theme in the history of pendulum-related science where it is seen that many different mechanical, biological and chemical processes can be understood as Simple Harmonic Motion and will accord with the SHM equation (Fig. 31.1).

Galileo used his Euclidean geometric constructions to give proofs of these laws, and then points to putative empirical evidence for them. Depicting the physical situation in terms of Euclidean geometry enabled Galileo to combine, and jointly prove, his iconic pendulum and inclined plane experiments. Inclined planes become chords inscribed in a circle whose diameter is double the length of a pendulum whose quarter swing defines the circumference and that terminate at the lowest point (Büttner 2019; Hahn 2002).

- LAW OF WEIGHT INDEPENDENCE: period is independent of weight.
- LAW OF AMPLITUDE INDEPENDENCE: period is independent of amplitude.
- LAW OF LENGTH: period varies directly as length; specifically, the square root of length.
- LAW OF ISOCHRONY: for any pendulum, all swings take the same time; pendulum motion is isochronous.

But these laws are not strictly true, as was soon pointed out to Galileo. They are true only in idealised circumstances.

In the First Day of his 1638 *Discorsi*, Galileo expresses his law of weight independence as:

> Accordingly, I took two balls, one of lead and one of cork, the former more than a hundred times heavier than the latter, and suspended them by means of two equal fine threads, each four or five cubits long. Pulling each ball aside from the perpendicular, I let them go at the same instant, and they, falling along the circumferences of circles having these equal strings for semi-diameters, passed beyond the perpendicular and returned along the same path. This free vibration repeated a hundred times showed clearly that the heavy body maintains so nearly the period of the light body that neither in a hundred swings nor even in a thousand will the former anticipate the latter by as much as a single moment, so perfectly do they keep step. (Galileo 1638/1954, p. 84)

In the Fourth Day of the 1633 *Dialogue*, Galileo states his law of amplitude independence, saying:

> … truly remarkable … that the same pendulum makes its oscillations with the same frequency, or very little different – almost imperceptibly – whether these are made through

> large arcs or very small ones along a given circumference. I mean that if we remove the pendulum from the perpendicular just one, two, or three degrees, or on the other hand seventy degrees or eighty degrees, or even up to a whole quadrant, it will make its vibrations when it is set free with the same frequency in either case. (Galileo 1633/1953, p. 450)

In the late fifteenth century, the great observer Leonardo da Vinci extensively examined, manipulated and drew pendulums, but as one commentator remarks: 'He failed, however, to recognize the fundamental properties of the pendulum, the isochronism of its oscillation, and the rules governing its period' (Bedini 1991, p. 5). This is significant: If the renowned observer, Leonardo 'The Lynx' as he was called, did not see the isochronism of pendulum oscillation, then 'seeing' it cannot be a simple matter for contemporary students. They need to be led to it by teachers who themselves can see; meaning who can appreciate the abstractions, idealisations and refined techniques required for such observation.

Although now routine and repeated in textbooks and often 'replicated' in school laboratory exercises, Galileo's claims were very contentious and disputed when first made. Much about science and the nature of science can be learned from these disputes about the legitimacy of mathematisation and idealisation in science. Students have the same problems that Galileo's contemporaries had: 'my experiment did not work', 'my pendulum stopped swinging', 'the light pendulum swung differently than the heavy one' and so on. Instead of the standard teacher responses of 'ignore the problem' or 'that was experimental error' – teachers having some historical and philosophical knowledge allow much more to be learnt about science and the nature of science from these discordant classroom situations. The situation is pregnant with NOS insight; it just needs a HPS-informed mid-wife for it to be born.

31.3 A New Science and New Nature of Science: Galileo's Methodological Innovation

The seventeenth century's analysis of pendulum motion is a particularly apt window through which to view the methodological heart of the scientific revolution. The debate between the Aristotelian Guidobaldo del Monte – who was Galileo's own patron who had secured for him positions at the universities of Pisa and Padua – and Galileo over the latter's pendular claims represents in microcosm the larger methodological struggle between old Aristotelian science and the new science. This struggle is about the legitimacy of idealisation in science and the utilisation of mathematics in the construction and interpretation of experiments (Hahn 2002; Lennox 1986; Matthews 2004; Nola 2004). Unfortunately, all students are in the position of da Vinci and del Monte. Without methodological input, hopefully from teachers, they will not see what Galileo 'saw'.

Del Monte was one of the great mathematicians and mechanics of the late-sixteenth century. He was a translator of Archimedes, a highly competent mechanical engineer and Director of the Venice Arsenal. Additionally, he was an accomplished artist, a minor noble and the brother of a prominent cardinal (Meli 1992). He and Galileo exchanged many letters and manuscripts on broadly Archimedean themes. Del Monte believed that theory should not be separated from application and that mind and hand should be connected. As he said in the Preface of his *Mechanics*: 'For mechanics, if it is abstracted and separated from the machines, cannot even be called mechanics' (Drake and Drabkin 1969, p. 245).

Del Monte is committed to the core Aristotelian principle that physics, or science more generally, is about the world as experienced and that sensory evidence, especially observation, is the bar at which putative physical principles are examined. This is also the commonsense understanding of science. Del Monte told Galileo that he was a great mathematician, but that he was a hopeless physicist. This is the methodological kernel of the Scientific Revolution. The subsequent development of pendulum analyses by Huygens, and then Newton, beautifully illustrate the interplay between mathematics and experiment so characteristic of the emerging Galilean–Newtonian Paradigm – a far more important GNP than most economic ones.

The crucial surviving document in the exchange between Galileo and his patron is a long 1602 letter (Galileo 1602/1978) in which Galileo writes of his discovery of the isochrony of the pendulum, conveys his mathematical proofs of the 'pendulum laws' and concludes 'I have been too long and tedious with you; pardon me, and love me as your most devoted servitor' (Drake 1978, p. 71). Many commentators discuss this exchange (Büttner 2019; Humphreys 1967; Naylor 1980).

Del Monte was not impressed by Galileo's proofs, claiming that Galileo was a better mathematician than a physicist. Many shared this view. Reasonably enough, del Monte could not believe that one body would move through an arc of 10 or 20 metres in the same time as another, suspended by the same length of string, would move through only one or two centimetres. Further, he conducted experiments on balls rolling within iron hoops and found that Galileo's claims were indeed false: balls released from different positions in the lower quarter of the hoop reached their nadir at different times; their paths were not isochronic. This then is the methodological basis for del Monte's criticism of Galileo's mathematical treatment of pendulum motion: the real world was different from Galileo's 'world on paper'. Del Monte reflects Aristotle's empiricism: his view that 'if we cannot believe our eyes, what can be believe?'

As early as 1636, the notable mathematician, natural philosopher and theologian Marin Mersenne (1588–1648) reproduced Galileo's experiments and not only agreed with del Monte but doubted whether Galileo had ever conducted the experiments (Koyré 1978, pp. 113–117). Modern researchers have duplicated Galileo's experimental conditions and have found that they do not give the results that he claimed (Ariotti 1968; Naylor 1989). Students in classrooms do not get the results either, unless care has been taken to highly refine the situation and to 'make allowance' for impediments.

It is easy to appreciate the empirical reasons for opposition to Galileo's law. The overriding argument was that if the isochronous law were true, pendulums would be perpetual motion machines, which they are not. An isochronous pendulum is one in which the period of the first swing is equal to that of all-subsequent swings: This implies perpetual motion. We know that any pendulum, when let swing, will very soon come to a halt; the period of the last swing will be no means the same as the first. Furthermore, it was plain to see that cork-and-lead pendulums have a slightly different frequency and that large amplitude swings do take somewhat longer than small-amplitude swings for the same pendulum length. All of this was pointed out to Galileo, and he was reminded of Aristotle's basic methodological claim that the evidence of the senses is to be preferred over all other evidence in developing an understanding of the world (Palmieri 2009).

The empirical problems were examples where the world did not 'correspond punctually' to the events demonstrated mathematically by Galileo. In his more candid moments, Galileo acknowledged that events do not always correspond to his theory; that the material world and his so-called 'world on paper', the theoretical world, did not correspond. Immediately after mathematically establishing his famous law of parabolic motion of projectiles, he remarks that:

> I grant that these conclusions proved in the abstract will be different when applied in the concrete and will be fallacious to this extent, that neither will the horizontal motion be uniform nor the natural acceleration be in the ratio assumed, nor the path of the projectile a parabola. (Galileo 1638/1954, p. 251)

One can imagine the reaction of del Monte and other hardworking Aristotelian natural philosophers and mechanicians when presented with such a qualification. It confounded the basic Aristotelian and empiricist objective of science, namely to tell us accurately about the world around us. The law of parabolic motion was supposedly true but not of the world we experience: this was indeed as difficult to understand for del Monte as it is for present-day students (Pólya 1977, pp. 100–105).

The fundamental laws of classical mechanics are not verified in experience; further their direct verification is fundamentally impossible. Herbert Butterfield (1900–1979) conveys something of the problem that Galileo and Newton had in forging their new science:

> They were discussing not real bodies as we actually observe them in the real world, but geometrical bodies moving in a world without resistance and without gravity – moving in that boundless emptiness of Euclidean space which Aristotle had regarded as unthinkable. In the long run, therefore, we have to recognise that here was a problem of a fundamental nature, and it could not be solved by close observation within the framework of the older system of ideas – it required a transposition in the mind. (Butterfield 1949/1957, p. 5)

The law of inertia contradicts all experience; evolution defies commonsense; claims about a spinning and orbiting earth are falsified in every waking moment. Investigation of the pendulum's properties puts classroom flesh on this philosophical claim (Wolpert 1992). There is a whole world of philosophy that can here be opened for students to investigate and discuss: what role does brute experience play in knowledge of the world? Does modern science operate with the same or different understandings of this role from indigenous sciences?

A major lesson to be learnt about the nature of science is that:

 # Scientific claims are usually not manifest in everyday experience, they mostly defy common sense.

31.4 Huygens Refinement of Galileo's Claims

Christiaan Huygens (1629–1695) refined Galileo's theory of the pendulum. He showed mathematically that the cycloid, not the circle, was the curve for isochronous motion. As shown in Fig. 31.2, the cycloid is the curve described by a point P rigidly attached to a circle C that rolls, without sliding, on a fixed line AB. The full arc ABD has a length equal to $8r$ (r = the radius of the generating circle). A heavy point which travels along an arc of cycloid placed in a vertical position with the concavity pointing upwards will always take the same amount of time to reach the lowest point, independent of the point from which it was released (Fig. 31.2).

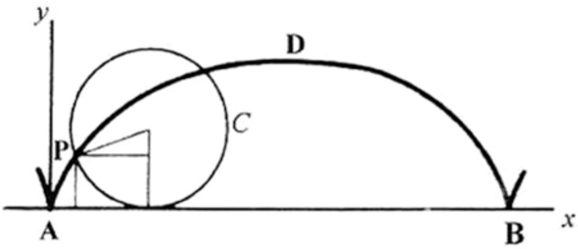
He says: 'Of interest to us is what we have called the power of this line to measure time, which we found not by expecting this but only by following in the footsteps of geometry' (Huygens 1673/1986, p. 11).

As with Galileo, science for Huygens progressed in virtue of mathematics progressing; this has been the pattern of all modern science. One need only think of the indispensable role of geometry, calculus and statistics in science to see the truth of this claim (Pólya 1977). After showing that the period of a pendulum varied as the square root of its length, Huygens then derived the following equation now familiar to all physics students:

$$T = 2\pi \sqrt{(l / \mathrm{g})}.$$

The mathematics utilized by Galileo, Huygens and Newton in their treatment of the pendulum is nicely laid out by George Pólya (Pólya 1977, pp. 125–138). This provides rich material for coordination between science and mathematics teachers.

Fig. 31.2 Cycloid curve



31.5 Huygens Pendulum Clock

Huygens realised that such an isochronic motion could be the regulator for a new and accurate clock: the pendulum clock which he proceeded to make, with which he hoped to win the various longitude prizes offered by all European governments and monarchs (Sobel 1995). Having shown mathematically that the cycloid was isochronous, Huygens then devised a simple way of making a suspended pendulum swing in a cycloidal path – he made two metal cycloidal cheeks and caused the pendulum to swing between them. Huygens first pendulum clock was accurate to 1 min per day; working with the best clockmakers, he soon made clocks accurate to 1 s per day. In the following century, pendulum clocks became accurate to within 1 s in 100 days.

31.6 The Proposal of an International Length Standard

In Huygens equation for the period of a pendulum, it looked as if the only variable was $\mathbf{L}$, as $\boldsymbol{\pi}$ was a constant and, provided one stayed near to sea level, $\mathbf{g}$ was constant, and mass did not figure in the equation at all. Consequently, all pendula of a given length will have the same period, whether they be in France, England, Russia, Latin America, China or Australia. Huygens was clever enough to see that the pendulum would then solve not only the timekeeping and longitude problems but an additional vexing problem, namely, establishing an international length standard. In 1673, he proposed the length of a seconds pendulum (a pendulum that beats in seconds; i.e., whose period is 2 s) to be the international unit of length. The length of the seconds pendulum was experimentally determined by adjusting a pendulum so that it oscillated 24 × 60 × 60 times in a sideral day; that is, between successive transits of a fixed star across the centre of a graduated telescope lens (the sideral day being slightly longer than a solar day). The task is not as daunting as it seems, as counting for just 1 h, and then extrapolating, suffices (Meli 2006, p. 205).

Having an international or even a national unit of length was a major contribution to simplifying the chaotic state of measurement existing in science and everyday life. Within France, as in other countries, the unit of length varied from city to city, and even within cities. This was a not insignificant problem for commerce, trade, construction and technology; to say nothing of science. Many attempts had been made to simplify and unify the chaotic French system. The Emperor Charlemagne in 789 issued an edict calling for a uniform system of weights and measures in France. One estimate is that in France alone there were 250,000 different, local, measures of length, weight and volume; and merchants had different measures depending on whether they were buying or selling; 'buy short, sell long' was the adage (Alder 1995, p. 43).

In the above formula, it is easy to ascertain that the length of a seconds pendulum (i.e., where $T = 2$) will be 1 metre. Using standard approximations for $\boldsymbol{g}$ (9.8 ms^2)

and π (3.14), it is easy to show that the length of a seconds' pendulum will be 1 metre.

$$T = 2\pi\sqrt{(l/\mathrm{g})}$$

$$T^2 = 4\pi^2 l/\mathrm{g}$$

$$l = T^2\mathrm{g}/4\pi^2$$

Substitute $T = 2$ s (each beat is a second), $\mathrm{g} = 9.8$ ms^2, $\pi^2 = 9.8$.
Then $l = 0.993577$ m, or very approximately 1 m,

Students can easily see this by taking any 1-metre-long simple pendulum and timing 10 or 20 swings, which will be seen to take 20 or 40 s (a heavy nut or stone on the end of a string suffices as the bob).

And with a universal length standard, volume and mass standards can easily enough be established. The mass (weight) of a 10 cc × 10 cc × 10 cc (1 litre) of rain water will be constant no matter where it is collected. This will be 1 kg. A great virtue of the seconds pendulum as the international length standard was that it was a fully 'natural' standard; it was something fixed by nature, unlike standards based on the length of a king's foot or the distance covered in 1000 steps of a Roman legion. Students can be encouraged to themselves work out how one might get from a standard unit of length to a standard unit of volume to a standard unit of weight. They can also do their own research on indigenous length, volume and weight standards and itemize the benefits of the now near-universal modern metric system.

31.7 Using the Pendulum to Determine the Shape of the Earth

Huygen's proposal of the seconds pendulum as an international standard of length assumed that **g** be constant around the world (at least at sea level). This seemed an indubitable assumption as the earth was surely spherical. Indeed, to say that the earth was not spherical was tantamount to casting aspersions on the Creator: surely God the Almighty would not make a misshapen earth. But in 1673, contrary to all expectation, this assumption was brought into question by the time variation in swinging of a seconds pendulum.

In 1672–1673, Jean Richer sailed to Cayenne in equatorial French Guiana to conduct astronomical observations for the *Académie Royale des Sciences*. But it was an unexpected consequence of Richer's voyage which destroyed Huygens' vision of a universal standard of length 'for all nations' and 'all ages'. Richer found that a pendulum set to swing in seconds, at Paris, had to be shortened to swing in seconds at Cayenne. Not much – 2.8 mm, about the thickness of a matchstick – but nevertheless shortened. Richer found that a Paris seconds- clock apparently lost 2½ min daily at Cayenne (Matthews 2000, pp. 144–147).

31.8 The Nature of Science Illustrated in the Testing of the Spherical Earth Theory

Richer's claim that the pendulum clock slows in equatorial regions nicely illustrates some key methodological matters about science, about theory testing, and consequently about the nature of science. The entrenched belief since Erastosthenes in the second century BC was that the earth was spherical (theory T), and on the assumption that gravity alone affects the period of a constant length pendulum, the observational implication was that period of a seconds pendulum at Paris and the period at Cayenne would be the same (O). Thus, T implies O:

$$\mathrm{T} \rightarrow \mathrm{O}.$$

But Richer seemingly found that the period at Cayenne was longer (~O). Thus, on simple falsificationist views of theory testing such as enunciated first by Huygens himself and famously developed by the philosopher Karl Popper early in the twentieth century (Popper 1934/1959), we have:

T → O	Theory (earth is spherical) implies Observation (seconds pendulum is constant length over whole globe)
~O	Observation statement is false (seconds pendulum needs be shorter at equator)
∴ ~T	Therefore, theory is false (*modus tollens* rule)

But theory testing is never so simple. In the seventeenth century, many upholders of T just denied that the second premise (~O) was true. The astronomer Jean Picard, for instance, did not accept Richer's findings. Rather than accept the message of varying gravitation, he doubted the messenger. Similarly, Huygens thought that it was Richer's experimental ability, not gravity, that was weak in Cayenne.

It is now more clearly recognised by philosophers that theories do not confront evidence on their own; there was always 'other things being equal' assumptions made in theory testing. There are ceteris paribus clauses (C_i) that accompany the theory into the experiment (Earman et al. 2002). These clauses characteristically included statements about the reliability of the instruments, the competence of the observer, the assumed original empirical state of affairs, theoretical and mathematical devices used in deriving O, and so on. Thus:

T + C → O	Theory and Conditions imply Observation
~O	Observation statement is false
∴ ~T or ~ C	Therefore, theory is false or stated conditions are false

$$\mathrm{T} + \mathrm{C} \rightarrow \mathrm{O}.$$

$$\sim O$$

$$\therefore \sim T \text{ or } \sim C.$$

Seventeenth-century natural philosophers maintained belief in T and said that the assumption that other things were equal was mistaken. There were a number of obvious items in C that could be pointed to as the cause of the equatorial pendulum slowing:

C^1 The experimenter was incompetent.
C^2 Humidity in the tropics caused the pendulum to slow because the air was denser.
C^3 Heat in the tropics caused the pendulum to lengthen, hence it beat slower.
C^4 The tropical environment caused increased friction in the moving parts of the clock.

These, in principle, were legitimate concerns. Each could account for the slowing and hence preserve the truth of the spherical earth theory. But each of them was in turn ruled out by progressively better controlled and conducted experiments. More and more evidence came in, and from other experimenters including Sir Edmund Halley, confirming Richer's observation of the slowing pendulum. Thus ~O became established as a scientific fact – as Fleck (1935–1979) would have said – and upholders of T, the spherical earth hypothesis, had to accommodate this evidence.

Many of course would say that some insignificant adjustment of the thickness of a match (3 mm) as a proportion of a metre (1000 mm) could just be attributed to experimental error, or simply ignored. And if the theory is important, then that is an understandable tendency to ignore discrepant facts: 'near enough is good enough' is the norm for pet personal, political, economic and religious theories. For more tough-minded scientists it seemed that the long held, and religiously endorsed, theory of the spherical earth had to be rejected. But Huygens could see a more sophisticated and plausible explanation for the lessening of **g** at the equator, which would preserve the spherical earth theory, namely:

C^5 Objects at the equator rotated faster than at Paris and hence the centrifugal (outward) force at the equator was greater, this countered the centripetal (inwards) force of gravity, hence diminishing the net downwards force (effective gravity) at the equator, hence decreasing the speed of oscillation of the pendulum; that is, increasing its period.

This final explanation for the slowing of equatorial pendulums which maintained the spherical earth theory was quite legitimate and appeared to save the theory. Many would be happy to pick up this 'get out of jail free' card and continue to believe that the earth was spherical. Huygens did not do so. He calculated the actual centripetal force at the equator and hence its effect on gravitational attraction. His mathematical calculations reduced the discrepancy to a mere 1.5 mm (Holton and Brush 2001, pp. 128–129). This is less than the thickness of a match, yet for such a minute discrepancy Huygens and Newton were prepared to abandon the spherical earth theory and state that the true shape of the earth was oblate. For the new quantitative science, the commonplace ‘near enough is good enough’ mantra could not be maintained; rather, ‘perfect is good enough’ became the norm that led to the ever-improving refinement of measuring instruments and experimental practice and controls (Wise 1995).

The Enlightenment *philosophe* Voltaire was hugely impressed with this and contrasted the actions of the natural philosophers with those of politicians, clergy and ideologues of every kind when confronted with even massive disconfirming evidence for their favoured positions. In Voltaire’s 1738 *The Elements of Isaac Newton’s Philosophy*, he wrote:

> Many Philosophers, on occasion of these Discoveries, did what Men usually do, in Points concerning which it is requisite to change their Opinion; they opposed the new-discovered Truth. (Fauvel and Gray 1987, p. 420)

The shape of the earth controversy is a wonderful episode in the history of science. A great pedagogical story, or even a dramatic enactment, can be made of it. All the elements are there: powerful and prestigious figures, ‘no name’ outsiders, controversy over a big issue, mathematics and serious calculations, religion, scientific and philosophical argument and persuasion, and final decision making with ample opportunity and reason to preserve the status quo. The shape-of-the-earth debate illustrates some key elements of the nature of science:

The dependence of science on technology.
The impact of external commercial factors on the growth of science.
The role of mathematics in scientific investigation.
The inter-dependence of scientific disciplines (mathematics, physics, astronomy).
The importance of being willing to rigorously and experimentally test accepted theory.
The unescapable requirement that theories are never tested in isolation, but always in company with explicit or implicit claims about accompanying conditions.
The need for replication of experiments and communication of results between scientists and across borders.

But sadly, the episode is little known and hardly ever taught. If history and philosophy are valued, then there is good justification for teaching the episode, but if ‘everyday, applied, immediate usefulness’ is the guiding principle for constructing science curriculum, then it is unlikely ever to be taught. Indeed, Noah Feinstein, an advocate of the ‘usefulness’ criteria for construction of science curricula has written:

> It [usefulness theory of curriculum] seems to suggest that the curriculum should be stripped of canonical content that students are unlikely to find relevant to their daily lives—such as, for instance, the shape of the earth. (Feinstein 2011, p. 183)

More is the pity for students not learning of this engaging and illuminating episode in the history of science; an episode that displays so well some crucial features of NOS, features that 'made science great' and that gave it its deserved status in the modern world.

31.9 The Pendulum in Newton's Physics

For Isaac Newton (1642–1726), the pendulum played a role comparable to what it had for Galileo (1564–1642) and Huygens (1629–1695). The pendulum linked this trinity of outstanding natural philosophers. Newton used the pendulum to determine the gravitational constant **g**, to improve timekeeping, to show the proportionality of mass to weight, to determine the coefficient of elasticity of bodies, to investigate the laws of impact, and to determine the speed of sound (Matthews 2000, chap. 8). Perhaps above all, he used the pendulum to demonstrate that the moon 'fell' towards to earth at the same rate that terrestrial objects fell to earth and so his law of gravitation was universal throughout the solar system; he unified celestial and terrestrial mechanics (Boulos 2006). This unification had hitherto, from ancient times, been ruled out on philosophical grounds – the heavens are a different kind of thing from the earth.

Accordingly, Richard Westfall, the distinguished Newtonian scholar, has written that: 'the pendulum became the most important instrument of seventeenth-century science … Without it, the seventeenth century could not have begot the world of precision' (Westfall 1990, p. 67). Concerning the pendulum's role in Newton's science, Westfall has said that 'It is not too much to assert that without the pendulum there would have been no *Principia*' (Westfall 1990, p. 82). And without Newton's *Principia*, the birth of modern science would have been much delayed, and who knows what shape it might have taken?

31.10 Conclusion

The pendulum, when taught with historical and philosophical awareness, provides an opportunity to learn about the nature of science and the interconnections of science–technology–society–culture, while one learns the subject matter of science. With HPS-informed teaching, the pendulum motion case enables students to appreciate the transition from common sense and empirical descriptions characteristic of Aristotelian science, to the abstract, idealised and mathematical descriptions introduced by Galileo and Newton that have characterised modern science (Blay 1998).

The pendulum provides a manageable, understandable and straightforward way into scientific thinking and away from every day and empirical thinking; it shows at the same time how scientific, idealized thinking nevertheless is connected with the world through controlled experiment. Without controlled experiment you do not have science.

The 'contextual' teaching of science is not a retreat from serious, or hard science, but the reverse. To understand what happened in the history of science takes effort. Further, it is appealing to students. A frequent refrain from intelligent students who do not go on with study in the sciences is that 'science is too boring, we only work out problems'. The history of human efforts to understand pendulum motion is far from boring: it is peopled by great minds, their debates are engaging, and the history provides a storyline on which to hang the complex theoretical development of science. As well as improved understanding of science, students taught in a contextual way can better understand the nature of science and have something to remember long after the equation for the period of a pendulum is forgotten.

References

Alder, K. (1995). A revolution to measure: The political economy of the metric system in France. In M. N. Wise (Ed.), *The values of precision* (pp. 39–71). Princeton: Princeton University Press.

Ariotti, P. E. (1968). Galileo on the isochrony of the pendulum. *Isis, 59*, 414–426.

Baker, G. L., & Blackburn, J. A. (2005). *The pendulum: A case study in physics*. Oxford: Oxford University Press.

Bedini, S. A. (1991). *The pulse of time: Galileo Galilei, the determination of longitude, and the pendulum clock*. Florence: Olschki.

Blay, M. (1998). *Reasoning with the infinite: From the closed world to the mathematical universe*. Chicago: University of Chicago Press.

Boulos, P. J. (2006). Newton's path to universal gravitation: The role of the pendulum. *Science & Education, 15*(6), 577–595.

Büttner, J. (2019). *Swinging and rolling: Unveiling Galileo's unorthodox path from a challenging problem to a new science*. Dordrecht: Springer.

Butterfield, H. (1949/1957). *The origins of modern science 1300–1800*. London: G. Bell and Sons.

Cohen, I. B. (1985). *Revolution in science*. Cambridge: Harvard University Press.

Drake, S. (1978). *Galileo at work*. Chicago: University of Chicago Press. Reprinted Dover Publications, New York, 1996.

Drake, S., & Drabkin, I. E. (Eds.). (1969). *Mechanics in sixteenth-century Italy*. Madison: University of Wisconsin Press.

Dupré, L. (2004). *The enlightenment and the intellectual foundations of modern culture*. New Haven: Yale University Press.

Earman, J., Glymour, C., & Mitchell, S. (Eds.). (2002). *Ceteris paribus laws*. Dordrecht: Kluwer Academic Publishers.

Fauvel, J., & Gray, J. (Eds.). (1987). *The history of mathematics: A reader*. London: Macmillan.

Feinstein, N. (2011). Salvaging science literacy. *Science Education, 95*, 168–185.

Fleck, L. (1935/1979). In T. J. Trenn & R. K. Merton (Eds.), *Genesis and development of a scientific fact*. Chicago: University of Chicago Press.

Galileo, G.: 1590/1960, De Motu. In I. E. Drabkin S. Drake (eds), Galileo Galilei on motion and on mechanics, University of Wisconsin Press, Madison, pp. 13–114.

Galileo, G. (1602/1978). Letter to Guidobaldo del Monte. In S. Drake (Ed.), *Galileo at work: His scientific biography* (pp. 69–71). Mineola: Dover Publications.

Galileo, G. (1633/1953). *Dialogue concerning the two chief world systems* (S. Drake, Trans.). Berkeley: University of California Press. (2nd Rev. ed, 1967).

Galileo, G. (1638/1954). *Dialogues concerning two new sciences* (H. Crew & A. de Salvio, Trans.). New York: Dover Publications. (orig. 1914).

Hahn, A. J. 2002, 'The pendulum swings again: A mathematical reassessment of Galileo's experiments with inclined planes', *Archive for the history of exact sciences 56*, 339–361.

Hall, B. S. (1978). The scholastic pendulum. *Annals of Science, 35*, 441–462.

Hodson, D. (2014). Nature of science in the science curriculum: Origin, development and shifting emphases. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 911–970). Dordrecht: Springer.

Holton, G., & Brush, S. G. (2001). *Physics, the human adventure. From Copernicus to Einstein and beyond*. New Brunswick: Rutgers University Press.

Humphreys, W. C. (1967). Galileo, falling bodies and inclined Planes: An attempt at reconstructing Galileo's discovery of the law of squares. *British Journal for the History of Science, 3*(11), 225–244.

Huygens, C. (1673/1986). *Horologium Oscillatorium. The pendulum clock or geometrical demonstrations concerning the motion of pendula as applied to clocks* (R. J. Blackwell, Trans.). Ames: Iowa State University Press.

Koyré, A. (1978). *Galileo studies*. Hassocks: Harvester Press. (orig. *Etudes Galiléenes,* 1939).

Lennox, J. G. (1986). Aristotle, Galileo, and the "mixed sciences". In W. A. Wallace (Ed.), *Reinterpreting Galileo* (pp. 29–51). Washington, DC: Catholic University of America Press.

Lindberg, D. C., & Westman, R. S. (Eds.). (1990). *Reappraisals of the scientific revolution*. Cambridge: Cambridge University Press.

Matthews, M. R. (1998). Opportunities lost: The pendulum in the USA National Science Education Standards. *Journal of Science Education and Technology, 7*(3), 203–214.

Matthews, M. R. (2000). *Time for science education: How teaching the history and philosophy of pendulum motion can contribute to science literacy*. New York: Kluwer Academic Publishers.

Matthews, M. R. (2004). Data, phenomena and theory: How clarifying the distinction can illuminate the nature of science. In K. Alston (Ed.), *Philosophy of education 2003* (pp. 283–292). Champaign: US Philosophy of Education Society.

Matthews, M. R. (2012). Changing the focus: From Nature of Science (NOS) to Features of Science (FOS). In M. S. Khine (Ed.), *Advances in nature of science research* (pp. 3–26). Dordrecht: Springer.

Matthews, M. R. (2014). Pendulum motion: A case study in how history and philosophy can contribute to science education. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 19–56). Dordrecht: Springer.

Matthews, M. R., Gauld, C. F., & Stinner, A. (Eds.). (2005). *The pendulum: Scientific, historical, philosophical and educational perspectives*. Dordrecht: Springer.

McComas, W. F. (2014). Nature of science in the science curriculum and in teacher education Programmes in the United States. In M. R. Matthews (Ed.), *International handbook of Research in history* (pp. 1993–2023). Springer, Dordrecht: Philosophy and Science Teaching.

Meli, D. B. (1992). Guidobaldo del Monte and the Archimedean Revival. *Nuncius, 7*, 3–34.

Meli, D. B. (2006). *Thinking with objects: The transformation of mechanics in the seventeenth century*. Baltimore: John Hopkins University Press.

Naylor, R. H. (1980). The role of experiment in Galileo's early work on the law of fall. *Annals of Science, 37*, 363–378.

Naylor, R. H. (1989). Galileo's experimental discourse. In D. Gooding et al. (Eds.), *The uses of experiment* (pp. 117–134). Cambridge: Cambridge University Press.

Nola, R. (2004). Pendula, models, constructivism and reality. *Science & Education, 13*(4–5), 349–377.

Olson, J. K. (2018). The inclusion of the nature of science in nine recent international science education standards documents. *Science & Education*, 1–24. https://doi.org/10.1007/s11191-018-9993-8onlinefirst.

Pagden, A. (2013). *The enlightenment and why it still matters*. Oxford: Oxford University Press.

Palmieri, P. (2009). A phenomenology of Galileo's experiments with pendulums. *British Journal for the History of Science, 42*(4), 479–513.

Pólya, G. (1977). *Mathematical methods in science*. Washington, DC: Mathematical Association of America.

Popper, K. R. (1934/1959). *The logic of scientific discovery*. London: Hutchinson.

Postman, N. (1999). *Building a bridge to the 18th century: How the past can improve our future*. New York: Alfred A. Knopf.

Pyenson, L. (1993). The ideology of Western rationality: History of science and the European civilizing mission. *Science & Education, 2*(4), 329–344.

Sobel, D. (1995). *Longitude: The true story of a lone genius who solved the greatest scientific problem of his time*. New York: Walker Publishing Company.

Westfall, R. S. (1990). Making a world of precision: Newton and the construction of a quantitative physics. In F. Durham & R. D. Purrington (Eds.), *Some truer method. Reflections on the heritage of Newton* (pp. 59–87). New York: Columbia University Press.

Wise, M.N. (Ed.): 1995, The Values of Precision, Princeton University Press, Princeton, NJ

Wolpert, L. (1992). *The unnatural nature of science*. London: Faber & Faber.

Wootton, D. (2015). *The invention of science: A new history of the scientific revolution*. London: Penguin Random House.

Chapter 32
Historical Inquiry Cases for Teaching Nature of Science Analytical Skills

Douglas Allchin

32.1 Science in Action and History

Imagine learning science alongside a famous scientist from history. Not just the concepts but also how science works. You are challenged to address the same problems and to participate in planning investigations, interpreting evidence, analyzing arguments, imagining alternative explanations, and assessing possible errors. For example, follow Nobel Prize winner Christiaan Eijkman as he searches for the cause of beriberi (Allchin 2013, pp. 165–183). Or accompany Alfred Russel Wallace as he plans a career collecting natural history specimens and puzzles about the origin of new species (Friedman 2010; see also text box below). Assume the role of Dave Keeling as he tries to measure precisely atmospheric concentrations of carbon dioxide—and secure funding to do so year after year for four decades (Leaf 2012). These are episodes of historical inquiry. The student who is able to reflect explicitly on the process learns scientific practices and the nature of science (NOS) firsthand, by modestly *doing science* (Hagen et al. 1996; Rudge and Howe 2009).

What is historical inquiry? It combines two familiar approaches to teaching NOS: (1) historical cases and (2) inquiry experience (with explicit reflection). It benefits from the merits of each approach while complementing their respective deficits (Allchin et al. 2014; see Table 32.1). First, history is valuable in contextualizing science, conveying its human and cultural dimensions. Historical narratives also show in detail how science unfolds. They reveal the complexity of laboratory and field practices, the role of chance (or accident), the fine-scale reasoning, as well as the large-scale debates. Historical stories excel especially where student inquiry activities tend to fail: they can cover long periods of

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_32

Table 32.1 Merits and deficits of modes of NOS instruction (from Allchin et al. 2014, p. 473)

Mode	Merits	Deficits
Contemporary case	Helps motivate engagement through authenticity and "here-now" relevance	Cannot be fully resolved, leaving uncertainty and incomplete NOS lessons
	Can support understanding of cultural, political, and economic contexts of science	Cannot exhibit details of process which are not yet public or are culturally obscured
	Can support understanding of how science and values relate	
	Develops scientific literacy skills in analyzing SSI	
Inquiry	Helps motivate engagement through personal involvement	Difficult to motivate all students, especially as a group
	Fosters personal integration of lessons	May be viewed as artificial exercise or school "game," not as genuine science
	Supports understanding of constructed interpretations, models, forms of evidence, and model revision	When investigations "fail," can prompt negative emotions, alienating student from NOS lessons
	Develops experimental competences: framing hypotheses, designing investigations, handling data, evaluating results	Typically shuttered off from cultural, social, or political contexts
	Relates nature of scientific knowledge to inquiry skills and methods	
	Develops understanding of how scientific claims can be defended or criticized in contemporary SSI cases	Hard to model role of "chance," or contingency
		Requires substantive amounts of time and resources
Historical case	Helps motivate engagement through cultural and human contexts and through narrative format	May seem "old" and irrelevant
		Difficult or time-consuming for teachers to learn background or historical perspective
	Can support understanding of long-scale and large-context NOS features: especially conceptual change, and cultural/biographical/economic contexts of research problems and interpretive biases	If text-based only, limits development of hands-on experimental competences
	Can support understanding of investigative NOS: problem-posing, problem-solving, persuasion, debate	If rationally reconstructed only or presented as final-form content, does not support understanding of "science-in-the-making"
	Can support understanding of complexity of scientific practice, as well as historical contingency	
	Supports analysis of process and product, since ultimate outcomes are known	
	When framed in inquiry mode, can develop scientific thinking skills—more efficiently than with hands-on inquiry	
	Can foster understanding of error and revision—without risking emotions of personal failure	

investigation—up to decades of research. Accordingly, they help convey the important NOS concepts of tentativeness, conceptual change, and the unexpectedness of such change—notoriously difficult to teach otherwise. By following the zigzag of historical development, and by fostering conceptual engagement through inquiry questions, students can be guided stepwise to grapple with the long-term change themselves. Historical cases have long been valued for providing insights into NOS.

At the same time, historical stories can seem remote—about another time and place, other people and other values not relevant today. Here precisely is where the second approach, student inquiry, offers value. According to the now-standard educational ideal (Schwab 1962), students take an active role in their own learning. They are challenged to think creatively and solve problems. By integrating inquiry into history, what would otherwise be a stale story, from a remote third-person perspective, becomes an embodied first-person experience, more memorable and effective from a learning perspective. NOS learning becomes more personalized and more effective.

Just as inquiry enhances the role of the history, the history can enhance the role of the inquiry. Too often, students dismiss their own inquiry activities as not "real" science. In historical inquiry, the problems emerge from original historical contexts. They are rooted in cultural and biographical realities. They help motivate *authentic* engagement (in contrast to decontextualized "black-box" activities or artificially contrived classroom inquires; Klassen and Froese Klassen 2013). With history, students come to understand naturally and vividly another central NOS feature—how science emerges from its social contexts and how its practices are shaped by cultural perspectives. In addition, history can provide the student with some of the intellectual resources to solve the inquiry challenges. After student effort, the history is also a benchmark for comparison. Finally, history delineates a productive path of successive inquiry challenges, not clear when the students act on their own. History thus helps enhance conventional inquiry.

What does historical inquiry look like in a classroom? A sample case—developed by a high school teacher collaborating with a historian of science—is described in the following text box (Friedman 2010). When biology textbooks discuss Darwin's theory of evolution by natural selection, they usually mention his travels on the *H.M.S. Beagle*. Many even discuss the influence of Lyell and Malthus on his thinking. However, historians are well aware that Alfred Russel Wallace independently developed a nearly identical theory on the origin of new species. The case study adapts Wallace's story for students to follow, highlighting his middle class background, his career as a collector, and the observations and experience that led to his own insights. The major NOS themes include:

- Diversity in scientific thinking
- The role of personal motives of scientists
- The importance of personal experiences and relationships of scientists
- Funding
- Communication in developing and presenting a theory
- Priority and credit

The basic format is a narrative built around a series of key questions (see more below). The questions—where the real learning is done—aim to engage students in explicit reflection about both the scientific concepts and the nature of science. This case also integrates optional supplemental activities already developed by the Natural History Museum of London, based on reading and reacting to Wallace's original letters. These can contribute further to underscoring the human dimension of science.

Alfred Russel Wallace & the Origin of New Species

by Ami Friedman

First, the teacher opens the case with a brief illustrated sketch of the cultural context in Britain in 1847. This helps to situate science in an accessible human setting. It also introduces some cultural themes that will be echoed later: the role of increased leisure time (that led to Wallace's love of reading about botany, insects, and evolution) and the role of the expanding railroad (which provided a job for Wallace as a surveyor, where he learned drafting skills and deepened his appreciation of geology and the outdoors).

Next, the teacher introduces the central scientific problem, along with the main character: Alfred Russel Wallace and uncertainties about how new species originate. The problem is also presented biographically: Wallace was trying to couple his personal study with collecting exotic animal specimens as a way to earn a living. The concrete human context helps to motivate the scientific inquiry by inviting the student to decide, alongside Wallace, how to finance his collecting expedition abroad. The life story also helps frame the conceptual resources available for students in their own thinking. The teacher pauses in the presentation to allow students time to think and discuss their responses.

The illustrated narrative then follows Wallace through his successive thoughts about evolution over the next decade. Student are thereby able to develop (or "construct") a concept of the origin of new species through natural selection step by step along with Wallace. There are numerous historical images and occasional quotes from Wallace's letters and autobiographical writings, giving first-hand testimony and vivid human dimension to the episode.

The narrative strings together a series of questions to actively engage students in and guide them through their conceptual development. For example, after Wallace's ship burns and he loses his valuable collection from the Amazon, students ponder whether to try again, collect elsewhere, or find other forms of employment, thereby highlighting the role of personal motives in science.

Other questions lead students into the process of scientific thinking. For example, assuming that Wallace wanted to explain similar species, their varieties, and any laws of nature that might explain them, what types of data

(continued)

would one collect on a voyage through the Amazon? Or, given some examples from South America and the Malay Archipelago, how might Wallace account for two similar types of organisms inhabiting neighboring areas at the same time, rather than in succession to one another? Later, when Wallace notices a series of forms with a large gap, how might he explain the lack of intermediates? These questions involve designing an investigation as well as interpreting evidence. All are situated with just enough background and information to allow students to reach plausible conclusions on their own, without prior knowledge of the scientific concepts. For each question, the teacher acts as a fellow participant and facilitates individual reflection and group interchange. Following discussion, the students are primed to hear how Wallace and his contemporaries reasoned.

The questions are situated historically. But they are also open-ended. Multiple answers are possible. The teacher encourages the students to think broadly. Without being accountable to just one "correct" answer, students more readily contribute to class discussion. In addition, the uncertainty underscores that science is about searching for and reasoning toward answers from the data at hand, not justifying some "right" answer that is already known.

One retrospective question asks students to compare Darwin and Wallace's ideas and histories. How should one interpret their parallel discoveries? Who should receive credit for discovering the concept of evolution by natural selection? Why? This nature of science feature—about priority and credit—involves a more synoptic perspective but again is open to several views.

As a conclusion, the teacher reprises the NOS elements explicitly. Students reflect on and articulate the influence of early encounters and life experiences on the practice of science, the role of personal motivation and opportunities, the challenge of funding, the role of scientific communication, and so on. This helps consolidate the NOS learning in the case and prepares students to apply their new knowledge to other cases. Perhaps they record what they have learned in a journal or in a written summary to submit to the teacher for review and comment.

[Summary adapted from Allchin 2012a, pp. 1264–1266]

32.2 History and Science-in-the-Making

Why not just tell historical stories? If history is a valuable source of NOS insight, why not just share NOS anecdotes or assign short vignettes or biographies to read, with the NOS concepts clearly stated and illustrated? Several websites are already beginning to make such stories readily available (www.storybehindthescience.org; www.science-story-telling.eu). While students will benefit to some degree, research on a variety of approaches to teaching NOS indicates that the most effective ones involve an element of inquiry (Bell 2007; Deng et al. 2011). This should not be surprising, given the general importance of inquiry learning. A key element is engaging the learner in the learning process and helping them make the lesson part of their individual cognitive structures. So the aim is to convert history into contextualized questions that specifically spur NOS inquiry.

Another reason to be skeptical about simple stories is the psychological tendencies of storytelling. Humans revel in telling stories. But the goal of entertainment and the desire to be viewed as informative can distort the truthfulness of the content. As a result, science stories tend to glorify scientific heroes, render their character and methods as more perfect than they really were, or monumentalize the achievement of one person at the expense of multiple contributors (Allchin 2003). Science storytellers easily fall prey to idealizations, or rational reconstructions, of the way science "should" have developed (Allchin 2000). As a result, the intended NOS lessons fall by the wayside. Teachers need to delve into the unexpected details of how discoveries actually occurred—sometimes as a result of chance encounters or unrelated developments—for students to be able to discern how science really works. So, the first challenge for teachers is to orient themselves to open questions that delve into the process of science, rather than present neatly prescribed historical "myths" about how science is "supposed to be" (Clough 2007).

In inquiry learning, the instructor's first task is to find questions or problems that will motivate students to *NOS* reflection and *NOS* learning. NOS (not just science) must be *problematized*. For example, "how do we know this evidence is reliable?" Or, "how might our reasoning be mistaken?" Teachers should demur from introducing NOS concepts pre-packaged. In addition, questions must be open-ended. No "teasers" with prescribed tenets that students are supposed to guess (or already know!). No leading the students by the nose to a target answer. History helps here. The key NOS questions are often found embedded in the history itself—another reason for replacing plain student-based inquiry with historical inquiry.

The second task of inquiry-style NOS instruction is to map an effective, loosely guided path from familiar concepts to new concepts. One recreates "science-in-the-making" (Latour 1987; Flower 1995; Allchin 2013, pp. 41–44). Textbooks provide only completed (readymade) science. In inquiry, teachers help students, like scientists, address unsolved problems, propose possible alternative solutions, and then assess and find ways to justify confidence in any answer. Working in that "blindness" is essential. It is very challenging for a teacher who already knows the textbook concept or the actual historical outcome. An instructor who adopts inquiry mode must learn to sacrifice the secure authority of already knowing the right answer or outcome. The focus instead is on the process, the reasoning, and the justifications—the very nature of science in constructing knowledge from scratch. Initially, most teachers struggle mightily to "not know" the right answer. It is hard not to give accidental clues or hints and to be as naive and full of wonder as the students. But it also generates an air of excitement, of suspense, and later the reward of insight. Again, working with this uncertainty in an inquiry environment and struggling toward developing an answer is an integral part of the NOS lesson, as modeled in history. The students are learning, through practice, just like their historical counterparts, what justifies confidence in a solution.

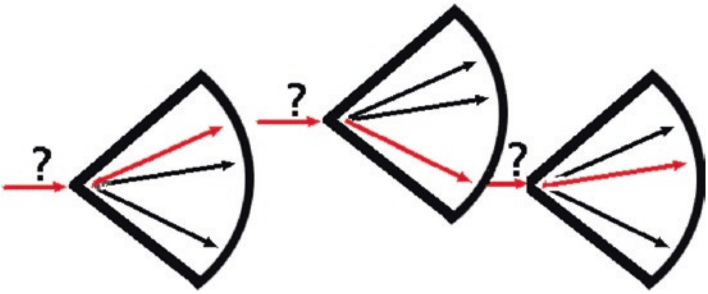

Fig. 32.1 The episodic nature of inquires—a lineage of questions—in a historical case, alternating between open questions and divergent responses

Combining history and inquiry may seem paradoxical. Inquiry learning is inherently open-ended. But the history is already done! It is closed. How can students experience the critical open-endedness in a context of closed history? The answers seem already known. Are the students merely to recapitulate, or repeat, the history, without any genuine input of their own? Are they expected to get the "right" answer—namely, just what history produced? What if they don't? Have they failed? (Without an instructor's guidance, that's exactly what students tend to think.) How can we reconcile open-ended inquiry with closed history?

Because openness and uncertainty are central to the learning process—and to the ultimate NOS lesson—the strategy is to work episodically, with a series of successive inquiries, each more narrowly focused (see Fig. 32.1). At each stage, teachers must give students complete freedom, including the freedom to "fail." It is the work on the individual problems and how they reason or exercise their creativity that matters. There are many possible ways to design a possible experiment for a given question. The history in each case can confirm this. There are usually multiple ways to interpret the results. Again, the history can confirm this. There are typically multiple potential flaws or weaknesses in any claim and multiple ways to respond to criticism. Again, history is a guide. These all enter student discussions and problem-solving. They enrich understanding of scientific practices or how science progresses somewhat blindly to produce reliable conclusions.

A major role for history is to help thread the inquiry episodes together. The history establishes the context for the first problem or question. Students engage in it. They compare solutions, even if they will *later* prove to be wrong. Then, the history is introduced. One learns the perspective of a selected central character (who need not always be correct!). One follows the narrative forward to the next occasion for inquiry. At each juncture, students are free (indeed, encouraged) to think openly. The story resumes with only one of the many possible trajectories, with the fate of all proposed solutions yet to be decided (Fig. 32.1)! The result is a lineage of *questions*, not just answers (Farber 2003).

As history unfolds, the uncertainties from early stages are resolved. Plausible alternatives are reduced as evidence accumulates. Debates are narrowed. Doubts and possible errors are addressed. Multiple forms of evidence converge. Eventually, a new concept emerges, and the students can justly celebrate having participated in its discovery. History is the episodic map for guiding students through an inquiry of science-in-the-making to its resolution.

32.3 Posing Authentic NOS Questions

As noted above, the key to any effective inquiry activity is motivating students at the outset with a good question or problem. Posing such questions is a familiar challenge for all teachers. Namely, how does one engage students in a strange new topic? Here is the great virtue of using history. History provides the critical motivation. One can usually engage student interest with a historical cultural context that makes the inquiry *concrete*, *meaningful*, and *worthwhile*. In addition, by focusing on particular scientists, one finds the biographical contexts (like Wallace's) that prompted someone to personally pursue research. These motivations—*in familiar human terms*—help shepherd students into investing effort in an inquiry activity. This contrasts with how a curriculum is typically characterized: by the *current* relevance of the concept. Ironically, the modern application is often not the original context that initiated the research that ultimately *led to* the concept. For example, the devastating 1906 San Francisco earthquake helped spur research into Earth's crustal movements (Dolphin 2009/2016). The aim was not to discover the yet-unknown plate tectonics. Carlton Gajdusek was motivated to find the cause of a strange disease among a remote tribe in New Guinea (Gros, 2011). The goal was not to discover a new mode of disease transmission. Marie Tharp—who eventually helped discover the mid-Atlantic rift—just wanted an interesting job (Elliott and Allchin 2016). Authentic historical questions help students model the process of doing science and, consequently, foster an understanding of how it works. Historical context is key.

Some popular NOS lessons are wholly decontextualized. They seem to focus on just one NOS concept, abstracted and divorced from the science which it intends to model. However, the artificial, highly contrived nature of such exercises is readily apparent to students, who tend to respond with indifference. They treat the activities as classroom games, not lessons about real science. Many educators regard these "black box" exercises as elegant, economic models of NOS. But that strong aesthetic relies on *already understanding the nature of science*. In a *teaching* context, with naive students, the abstract activities have limited effectiveness. That's why working on cases and authentic questions from history is so valuable. They are fully and richly contextualized. The motivation is real. Accordingly, students are engaged by familiar goals such as curing diseases, producing chemicals for profit, or wondering about the size of the universe.

Thus, the teacher's introduction of the historical problems or questions is not some trivial preamble to the "real" work. *Contextualizing the question through ren-*

dering the original scenario vividly is one of the instructor's most important roles in inquiry learning. So, one should not rush. Devoting ample time to setting the scene, using drama and emotion, is essential.

One fruitful way of closing a historical case is through a contemporary epilogue. How did the science from the past contribute to scientific research that is still continuing now? How did the *nature of* science from an episode in the past reflect how science functions in our society today? One needs authentic (and sometimes complex) cases to think analogically and to transfer NOS lessons to interpreting current claims about health or aging, the environment, or technological risk. Historically based NOS lessons are surely enhanced through retrospective reflection and re-contextualization in the present. That is part of completing the NOS lesson. And such meaningful connections are fostered through authentic NOS questions in real, fully contextualized historical cases.

32.4 Developing Lifelong NOS Analytical Skills

As articulated in the introduction to this volume, NOS education ultimately aims to help students interpret the reliability of sometimes contested scientific claims in personal and public decision-making. To assess those claims effectively, one needs to understand how science works. How are the claims assembled? How is their trustworthiness ensured? Equally, how can they fail? In what sense are they *tentative*? In what ways are they shaped by their *social or political milieu*? What is the *role of empirical evidence*, whether by *experiment or other form of investigation*? How are *inferences* involved and how does one gauge the soundness of the reasoning? NOS understanding is, ultimately, about supporting analytical thinking skills. It is not to recite or explain a list of NOS tenets. Active, inquiry-style learning is well adapted to the aim of developing skills for assessing the reliability of scientific claims (as discussed above). It engages students in exercising and practicing those skills. Students are also able to evaluate their own performance in reasoning and, through discussion with other students and instructors, adjust it and improve it. A focus on skills is another reason why working side by side with great scientists from the past can be so valuable.

Not surprisingly, perhaps, the dimensions of reliability in science reach far beyond the short NOS "consensus list" (Allchin 2017b). Some factors involve experimental reasoning, such as the use of controls or even ensuring that samples are not contaminated. Some involve conceptual factors, such as appropriate statistical tests or guarding against reasoning fallacies or the human psychology of confirmation bias. Others involve social dimensions, such as the credibility of the researcher or possible conflicts of interest in communicating science in the public realm. All are potentially important in assessing the reliability of a scientific claim. One can find recent cases in the news in which errors in each of these dimensions had major social consequences (see Allchin 2012b). So all are ultimately important for citizens to detect and understand. The consensus list is just an opening, highlighting some of the more significant elements. But to realize our educational vision, NOS education will cast its eye well beyond this narrow beginners' list to a much larger inventory of factors in how we ensure the reliability of scientific claims.

Historical case studies are ideal for expanding the focus on NOS, because the many different factors in assessing the scientific claims arise naturally in following each case closely. NOS questions, reflection, and problem-solving are easily incorporated into the authentic historical scenario. They each contribute to addressing the core question, "how do we know this?" "How can we be confident of the conclusion?" "Are there other alternative explanations?" "Are there potential sources of error to consider?" Cases from history are good samples of how scientific claims can be uncertain or controversial and how to address parallel claims today. Even a few historical cases each year, over a K-12 (or collegiate) education can provide a powerful foundation for addressing scientific claims in social settings. It's not just about the concepts. It's about the *skill* in analyzing scientific claims in the media.

The vast scope of NOS may seem overwhelming—and beyond the reach of even the most thorough education. That is why our deep goal should be to develop lifelong NOS thinkers. If we consistently underscore the theme of "how do we know this claim is reliable?", we can habituate students into a frame of asking the relevant questions. They will pose those questions even when they encounter NOS issues they have not experienced previously. And the very posture of asking those questions and seeking those answers is ultimately how we want to prepare students to become well-informed consumers and citizens. Historical inquiry cases help students learn NOS and NOS analytical skills.

32.5 Resources

Assembling effective case studies is exceptionally challenging. So the teacher first venturing into this realm might prudently plan, as a first step, to rely on prepared cases, rather than assemble their own. The novice should be on the lookout for cases with good, complex cultural and human contextualization. The questions should be compelling and open-ended. The scientific struggles should not seem too simple or obvious nor the characters too ideal—the history needs to be "honest" if the nature of science is also to be rendered authentically. One might also look for the role of a professional historian of science in writing or reviewing the case. Without well-written cases, one can, ironically, reinforce the very misconceptions one is trying to remedy (Allchin 2012a, 2013, pp. 46–120, 252–257). Fortunately, many good cases are already available. A sampling of cases ready for use in the classroom (already reviewed both by teachers and by professional historians and philosophers of science) is shown in Table 32.2. Other cases can be found at the SHiPS Resource Center website: http://shipseducation.net/modules.

Table 32.2 A sampling of good historical case studies for teaching aspects of NOS

Biology	
Christiaan Eijkman & the Cause of Beriberi	Allchin (2013, pp.165–183)
Alfred Russel Wallace & the Origin of New Species	Friedman (2010)
Carleton Gajdusek & Kuru	Gros (2011)
Modeling Mendel's Problems	Johnson and Stewart (1990)
Sickle-Cell Anemia & Levels in Biology, 1910–1966	Howe (2007, 2010)
Lady Mary Wortley Montagu & Smallpox Variolation in 18th-Century England	Remillard-Hagen (2010)
King D Carlos, A Naturalist Oceanographer	Faria et al. (2011)
Archibald Garrod & the Black Urine Disease	Gabel and Allchin (2017)
Richard Lower & the "Life Force" of the Body	Moran (2009)
Interpreting Native American Herbal Remedies	Leland (2007)
Picture Perfect?: Making Sense of the Vast Diversity of Life on Earth	Carter (2007)
Henry David Thoreau & Forest Succession	Rudge and Howe (2009)
Chemistry	
Determining Atomic Weights: Amodeo Avogadro & His Weight–Volume Hypothesis	Novak (2008)
Splendor of the Spectrum: Bunsen, Kirchoff & the Origin of Spectroscopy	Jayakumar (2006)
Karl Ziegler & Catalyzing Chemical Reactions	Allchin (2017a)
Physics	
Five Episodes in the History of Electricity	Henke and Höttecke (2010)
Contested Currents: The Race to Electrify America	Walvig (2010)
Robert Hooke, Hooke's Law & the Watch Spring	Horibe (2010)
William Thompson & the Transatlantic Cable	Klassen (2006)
Electromagnetism & the Telegraph	Barbacci et al. (2011)
The Snowflake Men	McMillan (2012)
Earth science	
Charles Keeling & Measuring Atmospheric CO2	Leaf (2012)
Evolution of the Theory of the Earth	Dolphin (2009)
Marie Tharp & Mapping the Ocean Floor	Elliott and Allchin (2016)
Debating Glacial Theory	Montgomery (2010)

References

Allchin, D. (2000). How *not* to teach historical case studies in science. *Journal of College Science Teaching, 30*, 33–37.

Allchin, D. (2003). Scientific myth-conceptions. *Science Education, 87*, 329–351.

Allchin, D. (2012a). The Minnesota Case Study Collection: New historical inquiry cases for nature of science education. *Science & Education, 21*, 1263–1282.

Allchin, D. (2012b). Teaching the nature of science through scientific error. *Science Education, 96*, 904–926.

Allchin, D. (2013). *Teaching the nature of science: Perspectives & resources*. St. Paul: SHiPS Education Press.

Allchin, D. (2017a). *Karl Ziegler & catalyzing reactions*. Minneapolis: SHiPS Resource Center. http://shipseducation.net/chem/ziegler.htm.

Allchin, D. (2017b). Beyond the consensus view: Whole Science. *Canadian Journal of Science, Mathematics and Technology Education, 17*, 18–26.

Allchin, D., Andersen, H. M., & Nielsen, K. (2014). Complementary approaches to teaching nature of science: integrating student inquiry, contemporary cases and historical cases in classroom practice. *Science Education, 98*, 461–486.

Barbacci, S., Bugini, A., Brenni, P., & Giatti, A. (2011). *The discovery of dynamic electricity and the transformation of distance communications*. Florence: Fondazione Scienza e Tecnica. http://hipstwiki.wikifoundry.com/page/Case+Study+1.

Bell, R. (2007). *Teaching the nature of science through process skills: Activities for grades 3–8*. Boston: Allyn & Bacon.

Carter, K. (2007). *Picture perfect?: Making sense of the vast diversity of life on Earth*. St. Paul: SHiPS Resource Center. http://shipseducation.net/modules/biol/lincei.htm.

Clough, M. P. (2007). Teaching the nature of science to secondary and post-secondary students: Questions rather than tenets. *The Pantaneto Forum*, *25* (January) http://www.pantaneto.co.uk/issue25/clough.htm

Deng, F., Chen, D.-T., Tsai, C.-C., & Tsai, C. S. (2011). Students' views of the nature of science: A critical review of research. *Science Education, 95*, 961–999.

Dolphin, G. (2009). Evolution of the theory of the earth: A contextualized approach for teaching the history of the theory of plate tectonics to ninth grade students. *Science & Education, 18*, 425–441.

Elliott, S., & Allchin, D. (2016). *Marie Tharp & mapping the ocean floor*. St. Paul: SHiPS Resource Center. http://shipseducation.net/modules/earth/tharp.htm.

Farber, P. (2003). Teaching evolution and the nature of science. *American Biology Teacher, 65*, 347–354.

Faria, C., Pereira, G., & Chagas, I. (2011). *A naturalist who became a pioneer of experimental marine oceanography in Portugal: Assets for science education*. Lisbon: University of Lisbon and The Aquarium Vasco da Gama. http://hipstwiki.wikifoundry.com/page/King+D+Carlos%2C+a+naturalist+oceanographer.

Flower, M. (1995). Conceiving science education as a practice of technoscientific practice. In F. Finley, D. Allchin, D. Rhees, & S. Fifield (Eds.), *Proceedings of the third international history, philosophy, and science teaching conference* (pp. 389–409). Minneapolis: University of Minnesota Office of Continuing Education.

Friedman, A. (2010). *Alfred Russel Wallace & the origin of new species*. St. Paul: SHiPS Resource Center. http://shipseducation.net/modules/biol/wallace.htm.

Gabel, K., & Allchin, D. (2017). *Archibald Garrod & the black urine disease*. St. Paul: SHiPS Resource Center. http://shipseducation.net/modules/biol/garrod.htm.

Gros, P. P. (2011). *Carleton Gadjusek & kuru*. St. Paul: SHiPS Resource Center. http://shipseducation.net/modules/biol/gajdusek.htm.

Hagen, J. B., Allchin, D., & Singer, F. (1996). *Doing biology*. Glenview: Harper Collins. http://doingbiology.net.

Henke, A., & Höttecke, D. (2010). *History of electricity*. Hamburg: University of Hamburg. http://hipstwiki.wikifoundry.com/page/history+of+electricity.

Horibe, S. (2010). *Robert Hooke, Hooke's law & the watch spring*. St. Paul: SHiPS Resource Center. http://shipseducation.net/modules/phys/hooke.htm.

Howe, E. M. (2007). Addressing nature-of-science core tenets with the history of science: An example with sickle-cell anemia. *American Biology Teacher, 69*, 467–472.

Howe, E. M. (2010). *Teaching with the history of science: Understanding sickle-cell anemia and the nature of science*. http://www1.assumption.edu/users/emhowe/Sickle_Case/start.htm

Jayakumar, S. (2006). *Splendor of the spectrum: Bunsen, Kirchoff & the origin of spectroscopy*. St. Paul: SHiPS Resource Center. http://shipseducation.net/modules/chem/spectro.htm.

Johnson, S., & Stewart, J. (1990). Using philosophy of science in curriculum development: an example from high school genetics. *International Journal of Science Education, 12*, 297–307.

Klassen, S. (2006). The application of historical narrative in science learning: The Atlantic Cable story. *Science & Education, 16*, 335–352.

Klassen, S., & Froese Klassen, C. (2013). Raising interest in interest: A critical component in learning science through stories and informal learning environments. In P. Heering, S. Klassen, & D. Metz (Eds.), *Flensburg Studies on the history and philosophy of science in science education* (Vol. 2). Flensburg: Flensburg University Press.

Latour, B. (1987). *Science in action*. Cambridge, MA: Harvard University Press.

Leaf, J. (2012). *Charles Keeling & measuring atmospheric carbon dioxide*. St. Paul: SHiPS Resource Center. http://shipseducation.net/modules/earth/keeling.htm.

Leland, T. (2007). *Interpreting Native American herbal remedies*. St. Paul: SHiPS Resource Center. http://shipseducation.net/modules/biol/native-herb.htm.

McMillan, B. (2012). The snowflake men. In P. Heering, M. Markert, & H. Weber (Eds.), *Experimentelle Wissenschaftsgeschichte Didaktisch Nutzbar Machen: Ideen, Ãœberlegungen Und Fallstudien* (pp. 45–65). Flensburg: Flensburg University Press.

Montgomery, K. (2010). *Debating glacial theory, 1800–1870*. St. Paul: SHiPS Resource Center. http://glacialtheory.net.

Moran, E. (2009). *Richard Lower and the 'life force' of the body*. St. Paul: SHiPS Resource Center. http://shipseducation.net/modules/biol/lower.htm.

Novak, L. (2008). *Determining atomic weights: Amodeo Avogadro & his weight-volume hypothesis*. St. Paul: SHiPS Resource Center. http://shipseducation.net/modules/chem/avogadro.htm.

Remillard-Hagen, E. (2010). *Lady Mary Wortley Montagu & smallpox variolation in 18th-Century England*. St. Paul: SHiPS Resource Center. http://shipseducation.net/modules/biol/smallpox.htm.

Rudge, D. W., & Howe, E. M. (2009). An explicit and reflective approach to the use of history to promote understanding of the nature of science. *Science & Education, 18*, 561–580.

Schwab, J. (1962). The teaching of science as enquiry. In J. Schwab & P. Brandwein (Eds.), *The teaching of science* (pp. 3–102). Cambridge, MA: Harvard University Press.

Walvig, S. (2010). *Contested currents: The race to electrify America*. St. Paul: SHiPS Resource Center. http://shipseducation.net/modules/phys/currents/pages/intro.htm.

Chapter 33
Teaching About Nature of Science Through Historical Experiments

Peter Heering and Elizabeth Cavicchi

33.1 Introduction

Having students experience historical experiments in the classroom is a powerful tool in teaching about the nature of science. Experiments performed by students support inquiry-based science instruction and have long provided an essential means of producing new scientific knowledge within science itself and throughout its history.

Students may be introduced to experiments by many instructional means. They may be asked to read and discuss written accounts of experiments (and experimenters) and historical publications based on experiments. Yet, such text-based instructional experiences do not engage students with procedural aspects of experimentation and related aspects of the nature of science (NOS). We argue that the procedure and process of science experimenting can only be conveyed through having students build their own experiences with experimenting and with reflecting on the nature of science.

Experiments from history can reveal the full range of characteristics of nature of science, as discussed in the cases below. Just as there is not one scientific method, there is also not one experimental method. Along with probing natural phenomena, experimental work is usually theory laden and open to controversy and creative interpretation. While history of science is a resource for teaching the nature of science (Matthews 2000; Allchin 2013), the specific context of historical experiments

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_33

augments historical accounts through the potentials of conducting experiments in classrooms (Kipnis 1996; Metz and Stinner 2007; Heering and Höttecke 2014). Performative aspects, such as how scientists stage experiments (and experimental reports), and material aspects (such as why particular materials were used, how the conceptual idea was materialized, what ascriptions applied to particular materials) elicit students' questions while they are initiating science experiments based on the history of science.

This chapter presents approaches by which historical experiments incorporated in science teaching bring about experiences and understanding of the nature of science for learners at differing stages in their education, from grade school to the graduate level and practicing teachers.

33.2 School Children Building Science Instruments

Schools, particularly lower secondary schools, normally have no access to historical instruments. In response to this reality, we decided to loan (reconstructed) instruments to teachers for a limited time. After students examined and analyzed these instruments, they drew on their findings, and the students then build their own version of the instrument and performed experiments with these setups. Among the instruments that were built by the students was a camera obscura with a lens and a water prism according to Goethe (for a detailed account, see Heering 2015). With the former device, students had two different options available (Fig. 33.1), one large instrument originally built in the Augsburg workshop of Georg Friedrich Brander (1713–1783) and the other being a much smaller instrument that was based on an instrument that had initially been in the possession of Johann Wolfgang Goethe.

Fig. 33.1 Two reconstructed camera obscura, one from the possession of Goethe (left) and the other from the Brander workshop (right)

Both devices had a lens and a mirror that reflected the image on a horizontally-mounted semipermeable glass plate, allowing the observer to see an upright image. While taking the working principle from these models, students realized that the instrument's dimensions are undetermined. The most important element was to have an adequate ratio between the dimension of the camera and the focal length of the lens that they used. In analyzing the instruments, students did not follow a step-by-step method. Rather, to be able to design their own version of the device, students had to understand its working principle. In developing their own analytical questions, as well as in making decisions on how to build their version of the device, students had to be creative. However, the intention of this approach lies not just in the reconstruction; students also should contextualize the instrument they build. Thus, in reflecting about the historical experiment together with the role of the device in that experiment which they also conducted, students are also enabled to reflect explicitly about physics.

From these activities, students realize that people with different skills and backgrounds are involved in scientific progress. In addition to the historical researchers mentioned in textbooks, people from diverse backgrounds, such as instrument makers, contribute to creating new scientific knowledge. While some are part of the academic culture, others are from cultures oriented around mechanical work and physical labor. Students come to understand that people from these different cultures participate in science. Through their experiences of reconstructing the instruments, materials, and experimental uses and principles in these projects, students recognize connections and distinctions between science and technology that figure in NOS studies.

33.3 Exchanges with Historical Experimenters and the Incomplete Story

For students' experimentation to be genuine research, they must be at liberty to develop their own questions and strategies. This liberty pertains to the nature of science characteristic that science and its history are not predetermined and closed to questioning. To engage students with questioning in science, Metz et al. (2007) authored accessible narratives of historical science which put students in the position of asking questions and making inferences about these stories. In one classroom strategy, termed "interrupted storytelling," teacher narrates a historical science story that poses a predicament. After students predict what may happen next, the teacher resumes the story, introducing further complications. We suggest adapting this approach to historical science experiments, by putting students in positions of developing their own questions about historical experiments. After students investigate, the teacher may narrate further from the historical experiment. As students consider ideas of their own and of historical characters, they reflect on the process of knowledge production in science.

To illustrate this strategy, we relate from three teachers' investigations of prisms, after reading Isaac Newton's letter (1671) on his prism experiments. In analogy to

Fig. 33.2 Left: Broad rainbow in bright patch on ceiling. Middle left: Rainbows in lines exiting apex of upright prism. Middle: Multiple hands orient prism and screen. Photo: Arnfinn Christensen. Middle right: Cardboard blocks light. Right: Block and two prisms

"interrupted storytelling," a follow-up activity could include asking participants to reconsider Newton's letter through their own experimental insights.

After discussing Newton's letter, each teacher took a glass prism (right-angled prisms; 6" long, 2" diagonal) and moved it in direct sunlight. Joy arose as they explored. Broad rainbows appeared on surrounding walls as the teachers rotated the prisms (Fig. 33.2, left). Prisms placed upright on the floor were stable, but broad rainbows no longer appeared. Instead, narrow rainbows extended out from a prism apex light (Fig. 33.2, middle left).

Yang was startled by mirror-like behavior of the prism; upon investigating the mirroring face, she found no light passed through. While Arnfinn employed science terms, "reflection," "refraction," and "total internal reflection," upon becoming surprised by what the prism did to light, he observed "it is interesting, very complicated. I expected it would be simple." Those science terms were initially meaningless. Through experimenting, teachers gained grounds for meaning; describing the prism's mirror behavior, its total internal reflection, Yang said "light is trapped."

The teachers asked question such as: "When do rainbows occur, and what do light rays do inside and outside the prism?", "Where does the rainbow come from?", and "What about an equilateral prism, like Newton's?" Collaboration arose spontaneously around these questions. Multiple hands positioned prisms and held screens to catch rainbows (Fig. 33.2, middle). Growing awareness of spatial relationships showed as teachers lifted the prism off the floor. Seeking rainbows, the teachers eventually succeeded through reorienting prisms in sunlight's path.

Anne Kristine exclaimed "I don't think Newton wrote down everything he did!" Devising her own method of blocking light which enters and exits the prism in order to isolate part of a light ray, to investigate its path (Fig. 33.2, middle right), Anne Kristine did not realize her blocking technique provides an analogue to how Newton selectively blocked light with a hole. The teachers introduced multiple prisms into their light paths (Fig. 33.2, right). Excited by how such growing systematism expanded their experimenting, Anne Kristine proposed "we are better than Newton! Now! What would be his answer if we wrote him a letter!"

This session's end interrupted their own ongoing story and its connection to Newton. The teachers initiated three experimental practices crucial to Newton's experiment: working out relative orientations of light beam and prism that produce rainbows; devising methods for blocking parts of a beam; and adding another prism to analyze light exiting the first. Encouraged by Newton's letter without grasping his procedure, and through being open in their own explorations, the teachers came into dialogue with Newton as capable coexperimenters. They experienced for themselves methods and creativity involved in experimenting with, and reasoning about, the lawlike behaviors of optics, aspects which are central in the nature of science.

33.4 Explorations with Light in Response to Historical Observations and Experiments

In cases described above, historical materials are introduced before learners reconstruct instruments and experiments. An alternative strategy, where learners first investigate science phenomena for themselves, is illustrated here by an example from optics. The teacher opens with a question; what students notice, and become curious about, is the source of explorations that they initiate with science materials. Next, students read accounts of historical experiments with the same phenomena. In response to readings, students discuss, experiment, and reflect. Students' personal experience with the science phenomena is their basis for questioning the historical experiments. Students act on these questions in experiments that they execute. In reflective writing, students' personal experiences inform insights (excerpts appear below) that relate to the nature of science as elaborated by educators.

During each phase – observation and exploring, reading, discussion, inference, experimenting, and reflective writing – students confront science phenomena that they did not expect and struggle with passages in historical texts. As students initiate science experiments that originate in their questions, they directly experience NOS methods of science including observation, inference, and interpretation. By doing science personally, and while working with others taking differing experimental paths, students experience firsthand how the process of science is not reducible to inexorable steps. Finding that historical readings carry descriptions and analyses that pertain today, students encounter the durable character of science. Confronting their tentative grasp of science phenomena, students discover that their questions, arising through subjective realization, are their means of building more robust understandings. Just as understanding in science is tentative, so too are the conclusions formed by students. By collaborating with classmates having differing perspectives, students discern diverse aspects of evidence. Students articulate multiple interpretations that facilitate collective questioning and discussions. In reflective writing, students realize themselves as participants in science, where classroom experience promotes understanding the nature of science.

Everyday materials accommodate provocative explorations which are accessible in any classroom. Light has boundless potential for classroom investigation yet is seldom observed closely. Light, shadows, and reflections are evidenced with daylight, cardboard, mirrors, shiny Mylar, paper, tape, string, scissors, and a darkened room. Observations of light occur in diverse ancient cultures, affording multiple entries, examples, and applications of lawlike behavior in optics.

Through witnessing properties such as reflection, and working out laws of optics, students encounter the remarkable consistencies of physics. In my (EC) example, light's equal angled reflection figured in diverse settings. Students observed that law in context, not as severed from the world. Recognizing that lawlike behaviors are evident within the natural world is foundational to understanding the nature of science.

An example from a science class illustrates this approach, where students explore mirrors, read about mirrors and their use in ancient times, and discuss, experiment, and engage in friendly arguments about things they encountered during this class study.

Students were first asked to explore by working in groups of 2–3 for over half an hour on the question, "where do you have to stand, so as to look in a small mirror taped to the wall and see in it someone standing at a different place from you?" (This activity was inspired by Hawkins (2000), Duckworth (1990), and Cavicchi (2009).) Provided with tape, a small mirror, and string, groups dispersed. After taping their mirror to a wall, students immediately found it disorienting to position themselves so they could view in it anything specific.

We find that confusion, such as about where to position themselves to see something specific in the mirror, intersperses with occasional success, which might first manifest as seeing any recognizable object in the mirror. Having first sighted something seemingly random, by iteratively readjusting position, the student eventually sees the intended target in the mirror. Students express confusion while experimenting; we encourage teachers to support their seemingly divergent conjectures and activities without speaking; to observe without directing; and to keep open the space which the students need in order for their thinking and observations to evolve. In doing so, the teacher demonstrates to students trust in the nature and process of science. That trust of the teacher will make possible trust in the students, who come to form robust understandings about science and realize they are participants in science.

In this example, upon finding arrangements by which two students mutually sighted each other, the student Peter marked those positions on the floor with tape. Eventually, Peter's group taped lines on the floor (Fig. 33.3, left): walking along these lines, a pair of students could see each other in it. These students disagreed about whether the walkers had to be at the same [perpendicular] distance from the mirror, in the same way that scientists would have to interpret evidence.

In the next class, discussion was lively. Lucienne, in Peter's group, said "you could see someone at the same angle as you, you could walk back and forth on that line and still see; distance didn't matter, but angle did." One classmate asked, "Can a short person see a tall person?" The class' shortest student, Samantha, who had paired with Andrew, the tallest, drew on the board. Her diagram, with a line bouncing between a tall and short person (Fig. 33.3, right), expressed the law of the mirror in a new context, not yet considered by others. Further discussion raised questions about the image seen in the mirror.

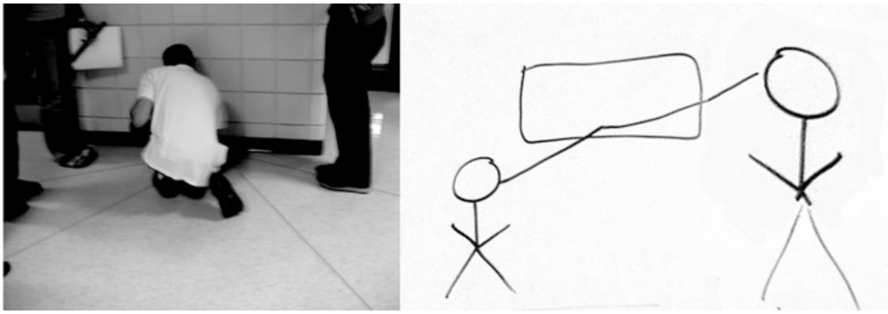

Fig. 33.3 Left: Student Peter Tusi (center) tapes lines on the floor. A mirror is above his head [not shown]. A student walking along the line to his right, while looking in that mirror, sees someone on the line to his left. Right: Samantha's drawing depicting herself [left figure] viewing taller Andrew [right figure] in the mirror [rectangle]

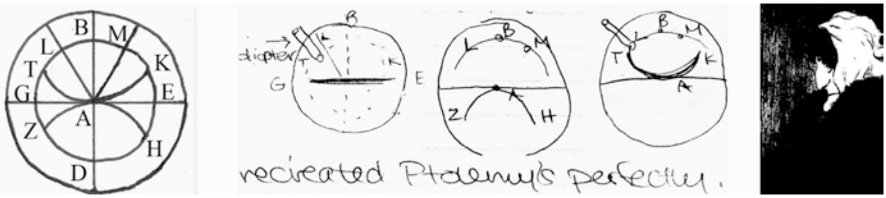

Fig. 33.4 Left: Ptolemy's top-view overlay diagram to demonstrate the equal angle property of a mirror. The observer sights object M looking through movable tube LA at flat mirror GAE; concave mirror TAK; convex mirror ZAH. Middle (next three circles): Samantha's diagrams apply Ptolemy's demonstration to flat mirror, convex mirror, and concave mirror (last circle) (Pitchel 2005). Right: The drawing simultaneously portrays a young woman and an old woman (Hill 1915)

Seeing these questions as productive, the teacher provided students with mirrors again. Improvising, they extended their observations. For example, coming upon the inverted reflections of print, Lucienne exclaimed "It's making me think more than before." This session ended with students listing relevant factors: angles of objects, mirror positions, and heights of observers.

In preparation for the next class, students were asked to read excerpts about optics from ancient classical texts (see Smith 1999 or Kheirandish 1999 for examples) and descriptions of how ancient mirrors were made (Melchior-Bonnet 1994; Needham and Ling 1962; Pigott 1992). Along with these readings, the assignment asked students to try the classical demonstrations. While historical language baffled some students, others found their way to a plausible interpretation. Composed of short historical readings, this assignment accommodated differing interests and comprehension. Samantha responded to Ptolemy (Fig. 33.4). Lucienne reacted to Roman artisan practice in initiating the class investigation of the size of one's face when viewed at differing distances from a mirror, as described below, after Samantha's personal study.

With its top-view diagram [Fig. 33.4, left], Ptolemy's demonstration of the equal angle property of reflection as a common property of flat, concave, and convex mirrors (Smith 1999) seemed inexplicable to Samantha. In representing all three cases as overlaid on the same diagram, the diagram emphasized the consistency of the law of equal angled reflection for all shapes of mirrors, but it was unserviceable as a guide to conducting the experiment in three dimensions with any one mirror. Thus the paradigm underlying the diagram's construction was disjoint from the outlook of Samantha seeking to perform the experiment. She moved in her thinking so as to reconstruct the experiment and to comprehend the paradigm that the diagram represents. In doing so, she experienced for herself the process by which science expands our understanding by means of multiple concurrent paradigms – in this case coordinating a theory-directed representation with an experimentally oriented one. Classmate Lucienne described attaining similar reversibility in perspectives through moving out of her "boxlike" fixation on the young woman in Hill's cartoon (Fig. 33.4, right), when classmate Devin supported her in tracing its lines to discover the old woman there too.

Samantha started by writing questions about Ptolemy's demonstration:

> [are mirrors] placed flat on ground?
> Leave all three mirrors up simultaneously?
> Or look at the object in each [mirror] one at a time?
> [if] simultaneously—how would you be able to see past first mirror to the other two?
> Exactly how are the mirrors to be set up? (Pitchel 2005)

Although Samantha considered that these questions left her "unable to fully recreate the experiment," in fact the rethinking of generating them was her opening to decode his text and "recreate Ptolemy perfectly" in a series of separate setups, one with each shape of mirror (Pitchel 2005; Fig. 33.4 middle). Similarly, teachers in the preceding example did not discern Newton's procedures from his letter, yet they reproduced key components of his experiment.

Samantha could not follow Ptolemy's text literally. By working with her sense of uncertainty and revisiting it on each next failure, she recreated not only arrangements of the mirror and objects but also the analysis of relationships that underlay the demonstration. Tracing her confusion along the way to reconstructing her interpretation, Samantha's notebook charts her process as an investigator reconstructing methods of science. In reflective writing, she wrote:

> [The historical] experiments had to be tried often, and with many subtle variations, in order to gain…understanding…In taking my notes, I was sure to record every detail, so I could go back to a certain piece and know how it was done and why. (Pitchel 2005)

A disequilibrating moment shared by the class came from a discussion about how Roman artisans (Melchior-Bonnet 1994) conserved metal by making the smallest mirror that showed a whole face. Lucienne explained why this historical practice was nonsense:

> If I used a little mirror, and set it up…and I backed away really really far, I bet that I could eventually see my whole body in that little mirror…. (Pierre 2005)

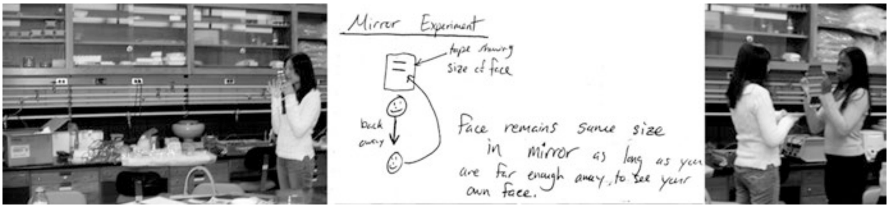

Fig. 33.5 Left: Anna (right) holds the mirror at her face level, while a classmate (not shown) views her face in it while walking left. Middle: Peter's diagram of tape on the mirror, around upper and lower outlines of the viewer's head (Tusi 2005). Right: Lucienne holds the mirror for Anna (left) who discovers, with the aid of the tape markers, that the size of her face does not change in the mirror reflection she sees

Jenniemae and Samantha, who tried this exercise at home, reported seeing their body appear further away but disagreed about its apparent size. In that uncertainty, the teacher perceived a basis for inviting the class to experiment. Imagining that further experimenting carried potential that students might reexamine such assumptions as underlying Lucienne's response to the Roman mirror, the teacher brought out a notebook-sized mirror and suggested using it in exploring a face's view.

The experiment began with Anna holding the mirror vertically, at her waist, while others took turns backing off (Fig. 33.5, left). This arrangement proved unworkable. Anna was asked to hold the mirror higher and higher until it was at the viewer's face level. Just as Samantha had encountered in responding to Ptolemy, many iterations were required before someone viewed their face throughout their entire displacement backing away from it. Samantha then proposed to put tape on the mirror around the viewer's face (Fig. 33.5, middle). Now, the persistence students had invested in backing up evenly gave way to astonishment. Having traded roles (Fig. 33.5, left), it was Anna viewing her face in the mirror who first observed and expressed the startling consistency. Speaking at first in tentative disbelief, her conviction grew in spontaneous exclamation:

> My face…It's weird. It still fits between the lines!

One after another, every student put themselves in the role of being the viewer and witnessing the same outcome. Even Lucienne, upon observing her face in the mirror, now affirmed the opposite of her original claim:

> Yeah. It stays the same.

The concurring observation of each student brought stability and coherence to the surprise that all felt – a surprise that carried awareness of inadequacy in their assumptions about the mirror.

The teacher raised the issue of making measurements. A ruler put to Anna's head, and to the taped mirror segment, gave almost a ratio of ½. When the teacher asked if the reference point on Anna's head was the same for taping and measuring, Lucienne averred it was not. Peter astutely expressed the disruptive shift in understanding involved in this experiment:

> …it [face in mirror] looks like a different size because you are further away so you look smaller to you, but in the mirror, you are still the same…size.

Classmates were amazed. Looking at a mirror is not like looking through a picture window. That their own actions were the means of bringing about that disequilibrating and self-correcting realization was significant to the students. It put students in the role of the original investigators, as Anna – discoverer of the reflection's property in this class – expressed in reflective writing:

> Science does not come from textbooks, it is an extension of our inherent curiosity and will to learn…When we are on our own and pondering [our experiments] we are indeed following the footsteps [of historical science]…our small, seemingly insignificant comments…in class over…a simple beam of light are important steps in the explorations of science. (Tsui 2005)

Having evolved a new understanding of light through experimenting grounded in her own questions and those of people in history, Anna reflected on what is involved in doing science firsthand. This personal experience grounded her eloquence in describing the nature of science, its methods, use of evidence, and creative insights.

The experience of being shown up, by the outcomes of experiments that he had initiated under expectations that came to be invalidated by his own evidence, was powerful for Peter. In contemplating this experience reflectively, Peter gained for himself the nature of science function of applying science experimenting as a tool in exposing false assumptions and facilitating self-correcting:

> Each unique experiment yielded something new…Some [classmates]…and I myself thought that I knew exactly what would happen. Needless to say…all of us, myself included, were dazzled when experiments had not gone as we had expected…it was the seemingly simple experiments that seemed to stun everyone the most when their basic assumptions proved false….
>
> Working through problems in a systematic way as we did a multitude of times, is an intriguing process…This critical problem solving, and self-correcting capacity is quite a useful tool. (Tusi 2005)

Having taken the risk of disputing the Roman mirror-makers, Lucienne brought herself and classmates into dialogue with nature, where nature's response took the form of evidence, revealed in how "the chips fall down":

> We were [in class] to learn about nature, history, and ourselves…in the most unexpected ways, letting the chips fall down where they may, and, if we could manage to pull ourselves away from the action long enough, note our observations…I felt like we were gaining the skills to be great innovators and investigators of the world around us. (Pierre 2005)

The dissonance between learners' assumptions and historical accounts of experiments provided openings for investigations initiated through learners' own questioning. Along with unearthing inadequacies in their assumptions, the students developed as practitioners of science, experiencing for themselves the nature of its experimental, theory building, reflective, and humanly interactive character.

At the same time that these students learned how science works and its nature through their firsthand experiments informed by history, they also expanded in awareness of what science is not, so as to recognize that science has limits. At the end of the course, in reflecting on the class' experimenting with the pendulum in response to Galileo's pendulum investigations (see also Cavicchi 2007, 2008, 2011, 2012), Lucienne acknowledged that initially, she had sought to "connect science with spirituality…a pendulum is like karma." After having done experiments establishing the law associating the length of pendulum string to its period, she no longer regarded pendulums as potentially bearing spirituality: "I don't know the answer to that question…pendulums are easier to understand than karma" (Pierre 2005). Particularly in experiments she performed with string and weights, bearing out the law that Galileo understood, Lucienne came to see science as provisional and dynamic, accessible through sense and reasoning in a community including classmates and scientists across history.

33.5 Teaching University Students About NOS Through Historical Experiments

Historical experiments are conducted by first year students who intend to be physics teachers at Europa-Universität Flensburg during their compulsory course on history of physics. Here, the students build a gnomon and take measurements with it; work with Galileo's inclined plane; carry out eighteenth-century electrostatic experiments; and perform electromagnetic experiments inspired by Oersted and Ampère. Likewise, historical experimenting was part of the education for teacher-students at the Carl von Ossietzky Universität Oldenburg (Heering 2003, 2009; Riess 1995, 2000). Historical instruments which these teacher-students used to experiment include Coulomb's electrical torsion balance; Ohm's electromagnetic torsion balance; magnetic apparatus of Gauss and Weber; Thomas Young's optical eriometer; and Count Rumford's experiments on radiant heat. Additionally, these students made experiences with eighteenth-century electrostatic experiments. Before each experiment, students read instructional materials (20 pages) on physics and historical background, with outlines covering advance preparations. The section below details how some experiments relate to understanding the nature of science.

The eriometer (George and Guarino 1973) has simple components: a candle, a screen pierced with one central hole with additional holes circumferentially arranged around the central hole, a device to hold the sample, and a ruler with an appropriate scale (Fig. 33.6). Passing through the central hole, light traverses a sample, such as wool. The (wool) structures diffract light, producing a diffraction pattern observed by the viewer. The size of particles (typically several μm) determines the pattern's diameter. The distance between the sample and the screen is adjusted so that the observational angle of the circular ring of holes in the screen corresponds to one of the (also circular) diffraction patterns. From the distance of the sample to the screen, the diameter of the particles in the sample can be inferred.

Thomas Young published papers on the eriometer, arguing for its applications in medicine and commerce. Neither contemporary scientists nor practitioners adopted it. Such thorough rejection might be attributable to an unreliable instrument. Making measurements with it, students obtained good results. The conceptual basis of the

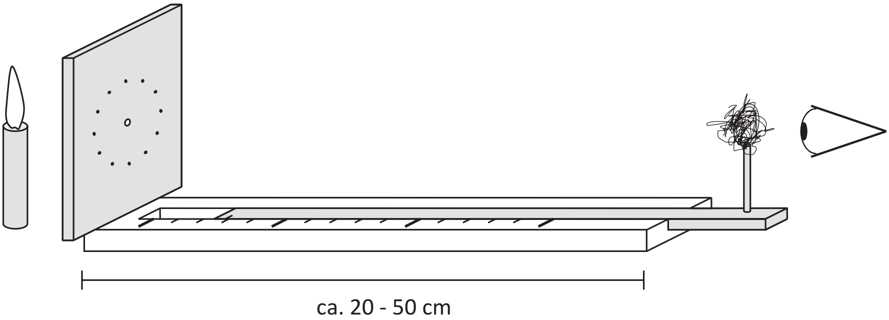

Fig. 33.6 Working principle of the eriometer (a device to measure the diameter of small particles through diffraction)

instrument provides clues to its rejection by contemporaries. Only a wave model of light can account for a diffraction pattern. In the early nineteenth century, Young advocated this theory. Influenced by Newton's particle model of light, the British scientific community dismissed evidence of light as a wave. Young's explanation and his instrument were rejected.

This example illustrates how science and technology impact each other and how observations are theory laden. As is typical for historical experiments, the experiment alone does not yield these insights. Observational experiences with the instrument, combined with historical contextualization, enable students in forming these NOS understandings. In retrospect, students reflect on their process. Initially, students cannot discern the diffraction patterns. Only through observational practice, and personal experience, do students develop the skills to see these patterns and make measurements. No explanation can short-circuit this process.

Learning to work with an eriometer bears similarities to working with a microscope. Both involve an image which cannot be projected; the image is formed in the observer's eye: one must learn to see the image. Students hardly can learn this NOS aspect through other means than personal experimenting and respective reflection upon processes involved. It is necessary for students to develop skills; students must be afforded time in order to develop those skills.

Under a naïve picture of experimenting, the experimenter approaches apparatus, performs the experiment, and produces results. Looking closer at experimental practices (either through practice or based on lab notes) quickly reveals that this image is completely misleading.

This issue of experience also applies to Galileo's inclined plane. When working with this device, students try to determine the position of the rolling ball in equal time intervals. Initially, this is challenging. With practice, students manage getting reasonable positions for the balls. In discussion with each other, students come to agree that the time intervals are equal – thus it is not an individual confidence that is developed but a collective one as is characteristic of science.

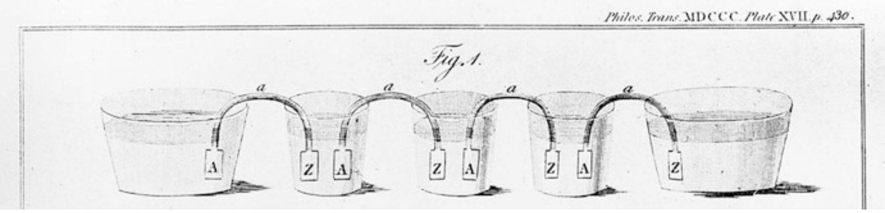

Fig. 33.7 Volta's "crown of cups" from the *Philosophical Transactions* in which Volta's letter to Joseph Banks was published. The letter was dated 20 March 1800. (Credit: Wellcome Library, London M0014526)

The crown of cups is an electrical device described by Volta, similar to his voltaic pile. Metallic strips are terminated at one end with copper plate and, at the other end, with zinc plate. A cup filled with salty water receives one end of the strip, and the strip's other end is immersed in the next cup. Cups, connected through metal strips, form a series of galvanic cells (Fig. 33.7).

Students can "feel" electricity by immersing fingers in cups, closing the electrical circuit. Student experiences differ. Some students are very sensitive to the shock and take only a few cells in series before stopping. At this point, others feel nothing and are able to stand the shock of more cells. Students notice that the human body is not that reliable in making statements about the strength of electricity – at least in making objective statements. Most students claim they have the impression of getting more sensitive in the course of the experience. Yet, what is crucial in these experiences is that practical interaction with the instrument forms a reason for discoursing. In this discoursing about their experiences, students develop insights in the nature of science. Their discussions consider whether this is electricity and how this phenomenon relates to static electricity (where everything has to be kept dry). This makes it evident that definitions in a field are tentative and that classifications are humanly constructed.

Lab activities based on electromagnetic experiments of Oersted and Ampère provide teacher education students with a different direction. A particular challenge in analyzing and describing the interaction between a magnet and a current in a wire (or currents in two wires) is the discussion of the orientation of the wires and the currents, the poles, etc. Ampère used spirals and coils to analyze these phenomena, and in doing so he employed an approach that Steinle describes in terms of exploratory experimentation (which is largely unconstrained by theoretical predictions yet still systematic; see Steinle 2016). At the end, a different type of experimentation is established based significantly on the theoretical understanding that has been developed. In this session students come to understand that there are different ways of experimenting: not only is there no universal method in the sciences; even in experimenting, different methods are employed.

One of us (PH) employs this NOS theme in a course at the Europa-Universität Flensburg that begins with the gnomon, a device originating 3000 years ago. During the last session, students visit a modern research lab with a clean room and helium ion microscope. Experiencing differences between historical and modern experimentation, students realize that scientific methods change over time.

In combining two sessions, one on the electrostatic experiments on discharges (Heering 2000) and the other enabling experiences with the torsion balance, the students immediately realized that the criteria for scientific experimentation change significantly over time. The discharging experiments are qualitative and phenomenon oriented and address a lay audience. This emphasis on the electrical phenomenon results both in a non-mathematical outcome of the experiments and a robustness of the experiments that were performed before audiences, or with audience participation. Coulomb's experiments are based on precision measurements; consequently the instrument is error-sensitive, which requires the exclusion of audiences. Laypersons are excluded through the results: a few quantitative data demonstrate a general mathematical relation. In contrasting these experiments, students realize immediately such significant differences as to conclude that there is not one experimental method.

33.6 Using the Historical Approach to Encourage Students' Own Research Projects

Another more individual approach relies on students being able to carry out their own research project. This project could be a BA or MA thesis, or a smaller undertaking. These students try to develop an understanding of how to perform a historical experiment. This understanding relates to scientific and practical components of experimenting and to historical context. By combining these areas through explicit reflections on their research, students develop understanding in the nature of science.

Graduate student Ruben Holländer carried out a thesis research project on the ignition of liquids through an electrical spark from an eighteenth-century electrostatic generator (Holländer 2017). Typically, the spark from a generator would ignite a liquid such as alcohol kept in a nearby spoon that was electrically grounded. Numerous accounts, including several images, depict this late 1740s experiment. On looking closer at these accounts, it becomes evident that several historical actors encountered difficulties when carrying out this experiment (cf. Heering 2014). These historical difficulties, combined with Holländer's preliminary experiments in which the liquid did not ignite, made it evident that he needed to investigate this situation systematically. Among the challenges he encountered in developing an understanding of the experimental procedures was the elaboration of the exact conditions: Which are the materials, particularly the liquids? Substances such as "Frobenius's Phlogiston…Peony-water, Daffy's Elixir, Helvetius's Stiptic…" (Watson 1744–45, 489f.) are no longer commonly known. Which conditions are relevant, and how can they be controlled? What about the humidity of the air, the temperature of the liquid, the geometry of the experiment, the amount of electrical charge, etc.?

In experimenting on these issues and returning to written sources, Holländer finally gained a coherent understanding of the requirements in order to perform the demonstration. Concurrently, he developed an understanding of the interplay between observation, empirical evidence, and rational arguments as well as skepticism. Skepticism became evident, as there were seemingly rules he developed during his study; later, he needed to question and in the end revise some of these initial rules.

Student Sonja Woltzen analyzed Jean Paul Marat's optical experiments from the early 1780s. Later renowned in the French Revolution, Marat was a natural philosopher who tried to modify Newton's theory of optical dispersion. Since Marat's experiments were rejected by the Paris Académie Royale des Sciences, historians assumed they were erroneous; Woltzen tried to reproduce the effects Marat described and eventually succeeded. She was able to interpret the effects in terms of modern optics. Her self-reflections elucidate the relation between theory and experiment:

> "…it is clarified through Marat's optical researches that the interpretation of certain observations can be based on various theories and that from isolated experiments the universal validity of a theory cannot be concluded." (Woltzen 2000, p.157, author's translation; see Heering 2004).

This reflection demonstrates that Woltzen not only engaged with a historical experiment; her engagement resulted in the formulation of key NOS aspects. Through her study, she explicitly stated that science requires evidence yet, at the same time, that scientific knowledge is tentative. Her historical analysis on the conflict between Marat and the Paris Academy reflects on social influences that characterize controversy about scientific experiments.

33.7 Concluding Remarks

We provide examples that demonstrate how the practice of redoing historical experiments in the classroom can involve learners of all ages in coming to grips with the nature of science. Learners' own experiences support them in making such realizations that scientific experimentation is a cultural activity dependent on time and place and shaped by social, philosophical, and political factors. Through contextualizing historical experiments, by having students contrast how similar experiments were done in different historical periods, learners come into contact with social and cultural influences on science and observe how subjectivity functions in the conduct of science. While experiments that originate in history can be demonstrated in decontextualized instructional formats, doing so deprives the experiments of much of their meaning and power to connect with students – particularly with respect to the nature of science.

The activity of experimenting with phenomena, materials, instruments, and cultural perspectives originating in history accommodates diverse and provocative openings to student curiosity and involvement. From these openings, students initiate and create together personal and collective experiences, such as how a class investigation of the size of a face, as viewed in a mirror at any distance, originated in Lucienne's incredulity about Roman mirror artisans' work. Being instigated by students themselves, their experiments pertain to their own questions, assumptions, confusions, and context. Students' experiments produce findings, evidence, and outcomes that challenge, surprise, and impact their understanding of the science and history that they set out to investigate and of the nature of learning and science. Having experienced for themselves the tentative yet durable and self-correcting character of scientific knowledge, the necessity of evidence, and the creativity of scientists (McComas 1998), students come to value the nature of science. Being empowered to experimental and reflective practice in their classroom and everyday life, students are prepared to extend the footsteps of past experimenters into the unknowns of their future.

Several studies involving historical experiments show their potential in science education explicitly, or suggest historical experiments as an opening for teaching NOS. Chang (2011) is certainly one of the most relevant ones; he considers applying his case studies in electrochemistry and thermodynamics to teaching the nature of science. Eggen and colleagues describe the potential of experimenting with a voltaic battery (Eggen et al. 2012). While describing many historical optics experiments, Kipnis (1993) did not elaborate on the nature of science; his materials could be adapted in this respect. Höttecke (2000) provides an excellent case study on very early electric motors that can be used in addressing mutual relations among science and technology and engineering. Höttecke et al. (2012) provide substantial proposals on implementing historical experiments in education, particularly addressing nature of science. Teichmann (1999) discusses reconstructing some Galileo experiments in the classroom.

Acknowledgment EC thanks learner-participants in optics experiments described above: Devin Bramhill, Anne Kristine Byhring, Arnfinn Christensen, Jennimae Cronan, Annamarie Fallon, Andrew Lix, Lucienne Pierre, Samantha Pitchel, Aaron Shaw, Anna Tsui, Peter Tusi, and Yan Yang.

References

Allchin, D. (2013). *Teaching the nature of science: Perspectives & resources*. Saint Paul: Ships Education Press.

Cavicchi, E. (2007). Mirrors, swinging weights, lightbulbs…: Simple experiments and history help a class become a community, 47-63. In P. Heering & D. Osewold (Eds.), *Constructing scientific understanding through contextual teaching*. Berlin: Frank & Timme.

Cavicchi, E. (2008). Opening possibilities in experimental science and its history: Critical explorations with pendulums and singing tubes. *Interchange, 39*, 415–442.

Cavicchi, E. (2009). Exploring mirrors, recreating science and history, becoming a class community. *New Educator, 5*(3), 249–273.

Cavicchi, E. (2011). Classroom explorations: Pendulums, mirrors and Galileo's Drama. *Interchange, 42*(1), 21–50.

Cavicchi, E. (2012). Explorando Péndulos en el Salón de Clases. In Z. Monroy-Nasr, G. Alvarez, & R. León (Eds.), *Enseñanza de la Ciencia* (pp. 27–50). México: Facultad de Psicología y DGAPA, UNAM.

Chang, H. (2011). How historical experiments can improve scientific knowledge and science education: The cases of boiling water and electrochemistry. *Science & Education, 20*(3), 317–341.

Duckworth, E. (1990). Opening the world. In E. Duckworth, J. Easley, D. Hawkins, & A. Hentriques (Eds.), *Science education: A minds-on approach for the elementary years* (pp. 21–59). Hillsdale: Lawrence Erlbaum.

Eggen, P.-O., Kvittingen, L., Lykknes, A., & Wittje, R. (2012). Reconstructing iconic experiments in electrochemistry: Experiences from a history of science course. *Science & Education, 21*(2), 179–189.

George, S., & Guarino, M. (1973). Young's eriometer: History and modern teaching use. *Physics Education, 8*(6), 392.

Hawkins, D. (2000). Critical barriers in science learning. In D. Hawkins (Ed.), *Roots of literacy* (pp. 179–200). Boulder: University Press of Colorado. (Original essay published in 1978).

Heering, P. (2000). Getting shocks: Teaching secondary school physics through history. *Science & Education, 9*, 363–373.

Heering, P. (2003). History – Science – Epistemology: On the use of historical experiments in physics teacher training. In W. McComas (Ed.), *Proceedings of the Sixth IHPST Conference Denver (Colorado)*.

Heering, P. (2004). Rejected historical experiments and their use for science teacher training. In D. Metz (Ed.), *Proceedings of the 7th International History, Philosophy of Science and Science Teaching Conference, Winnipeg, 2003* (pp. 366–376).

Heering, P. (2009). The role of historical experiments in science teacher training: Experiences and perspectives. *Actes d'Història de la Ciènca I de la Tècnica Nova època, 2*(1), 389–399.

Heering, P. (2014). The stabilization of experimental procedures: Historical and educational aspects. *Revista Brasileira de História da Ciência, 7*(2), 142–148.

Heering, P. (2015). Make–keep–use: Bringing historical instruments into the classroom. *Interchange, 46*(1), 5–18.

Heering, P., & Höttecke, D. (2014). Historical-investigative approaches in science teaching. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (Vol. 2, pp. 1473–1502). Dordrecht: Springer.

Hill W. E. (1915). My Wife and My Mother-in-Law. *Puck*, November 6, 1915, 11; in American Periodicals 73, 2018.

Holländer, R. (2017). *Die Entzündung brennbarer Flüssigkeiten mittels elektrischer Funken – eine historische und physikalische Analyse.* BA-Thesis, Europa-Universität Flensburg.

Höttecke, D. (2000). How and what can we learn from replicating historical experiments? A case study. *Science & Education, 9*, 343–362.

Höttecke, D., Henke, A., & Riess, F. (2012). Implementing history and philosophy in science teaching: Strategies, methods, results and experiences from the European HIPST project. *Science & Education, 21*(9), 1233–1261.

Kheirandish, E. (1999). *The Arabic Version of Euclid's Optics, Edited and Translated with Historical Introduction and Commentary*, 2 volumes, New York: Springer. Sources in the History of Mathematics and Physical Sciences, ed. G.J. Toomer, no. 16.

Kipnis, N. (1993). *Rediscovering optics*. Minneapolis: Bena Press.

Kipnis, N. (1996). The 'historical-investigative' approach to teaching science. *Science & Education, 5*(3), 277–292.

Matthews, M. R. (2000). *Time for science education: How teaching the history and philosophy of pendulum motion can contribute to science literacy*. New York: Kluwer Academic/Plenum Publishers.

McComas, W. F. (1998). The nature of science in science education: Rationales and strategies. In *Dordrecht*. Boston: Kluwer Academic Publishers.

Melchior-Bonnet, S. (1994). *The Mirror: A History* (K. H. Jewett, Trans.). New York: Routledge.

Metz, D., & Stinner, A. (2007). A role for historical experiments: Capturing the Spirit of the itinerant lecturers of the 18th century. *Science & Education, 16*(6), 613–624.

Metz, D., Klassen, S., McMillan, B., Clough, M., & Olson, J. (2007). Building a Foundation for the use of historical narratives. *Science & Education, 16*(3–5), 313–334.

Needham, J., and Ling, W. (1962), Science and Civilization in China, v 4, Cambridge: Cambridge University Press.

Newton, I. (1671). A letter of Mr. Isaac Newton…containing his new theory about light and Colors. *Philosophical Transactions, 6*, 3075–3087. http://www.newtonproject.ox.ac.uk/view/texts/normalized/NATP00006.

Pierre, L. (2005). *Assignments and notebook for Honors 290F*. Boston: University of Massachusetts Boston.

Pigott, V. (1992). Ancient metal-Mirror making in South India: Analyzing a mysterious alloy. *Journal of Metallurgy (JOM)*, 38–40.

Pitchel, S. (2005). *Assignments and notebook for Honors 290F*. Boston: University of Massachusetts Boston.

Riess, F. (1995). Teaching science and the history of science by redoing historical experiments. In D. Allchin (Ed.), *Proceedings of the third international history, philosophy, and science teaching conference* (Vol. 2, pp. 958–966). Minneapolis: University of Minnesota.

Riess, F. (2000). History of physics in science teacher training in Oldenburg. *Science and Education, 9*(4), 399–402.

Smith, A. M. (1999). *Ptolemy and the foundations of ancient mathematical optics: A source based guided study*. Philadelphia: American Philosophical Society.

Steinle, F. (2016). *Exploratory experiments: Ampère, Faraday, and the origins of electrodynamics* (A. Levine, Trans.). Pittsburgh University of Pittsburgh Press.

Teichmann, J. (1999). Studying Galileo at secondary school: A reconstruction of his 'Jumping-Hill' experiment and the process of discovery. *Science & Education, 8*(2), 121–136. https://doi.org/10.1023/a:1008653420325.

Tsui, A. (2005). *Assignments and notebook for Honors 290F*. Boston: University of Massachusetts Boston.

Tusi, P. (2005). *Assignments and notebook for Honors 290F*. Boston: University of Massachusetts Boston.

Watson, W. (1744–45). Experiments and observations, tending to illustrate the nature and properties of electricity: By William Watson, apothecary. *F. R. S. Philosophical Transactions, 43*(472–477), 481–501.

Woltzen, S. (2000). *Jean Paul Marats Experimente zur Farbentstehung: Nachbau einiger Instrumente, Nachvollzug ausgewählter Experimente und physikalische Diskussion*. Schriftliche Hausarbeit: Oldenburg.

Chapter 34
Teaching the Limits of Science with Card-Sorting Activities

Lena Hansson

34.1 Introduction: The Limits of Science Are Part of Nature of Science

What kind of questions could be asked/answered within science? Will all questions eventually get a scientific answer? Or are there questions that science will never be able to work with or answer? Thus, are there limits for science? How could these limits, in that case, be understood? There are different viewpoints on these and related issues. Thus, as on most nature of science (NOS) issues, there is not one agreed-on position on whether science has limits, and in case they exist, how these limits should be viewed upon.

From a logical positivistic point of view, one might suggest that there are no meaningful questions that could be asked that science cannot, at least in the future, answer. From such a viewpoint, many religious and ethical issues are viewed meaningless. Also among scientists there are people, such as Richard Dawkins, who question whether science has limits at all and argue that, for example, the issue of whether a god exist is a scientific question (Dawkins 2006). Such very optimistic views upon what science can achieve is sometimes called 'scientific expansionism', also labelled 'scientism' (Stenmark 2008). Stenmark states that: 'advocates of scientism believe that the boundaries of science ... could and should be expanded in such a way that something not previously understood as science can now become a part of science. ... Scientism, in its most ambitious form, can be defined as the view that science has no real boundaries – that it will eventually answer all empirical,

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_34

theoretical, practical, moral, and existential questions and will in due time solve all genuine problems humankind encounters'. (p. 113)

However, the position that science has no limits has been questioned by philosophers of science on different grounds, and a more common view among philosophers today is that science indeed has limits. This means that there are questions that fall outside the scope of science, even though well-defined demarcation criteria, which for example different philosophers of science can agree on, have been hard to construct (e.g. Curd et al. 2013; Turgut 2011). Questions that are outside the scope of science could include many religious, ethical and ideological issues. Stenmark (2017) discusses, from a philosophical perspective, science in relation to ethical and policy issues and states that "Science cannot tell us what we should do, only what we can do. It can tell us how the world 'is' but not how it 'ought' to be" (p. 11). Discussions of the issue of what separates scientific ideas from non-science (e.g. from religion, ethics and ideology), but also from pseudoscience (which has scientific claims) (Turgut 2011) are important when helping students understand issues of scope and limits. This chapter will deal with the limits between science and non-science, but not with the demarcation of science from pseudoscience.

As Nobel Prize winner Peter Medawar has pointed out, it is important to notice that stating that science has limits should not be understood as a way to downgrade science, but as a way to "exculpate science from the reproach that science is quite unable to answer those ultimate questions [which are] beyond the explanatory competence of science. /…/ To reproach it for its inability to answer all the questions we should like to put to it is no more sensible than to reproach a railway locomotive for not flying or, in general, not performing any other operation for which it was not designed" (Medawar 1984, p. xii).

Although it is the case that most philosophers of science today would argue that science cannot answer all types of questions, the legacy of logical positivism still influences science teaching (Aikenhead 2006; Poole 1995). Thus, the teaching of science does most often not communicate images of NOS questioning views associated with this legacy. Instead, frequently, science teaching communicates different stereotypical and mythical images of science (McComas 1998); see also Chap. 3 in this book. Some of these are, more or less, in line with logical positivism such as that "Science and its methods can answer all questions" (McComas 1998, p. 61). That is, science has no limits. When this is said in the name of science, it is often labelled scientism (Stenmark 2001; see also above). Such views upon NOS often constitute a hidden curriculum in the teaching of science (Hansson 2018). In line with this, Taber (2013) states that "there is much potential for the image of science offered to pupils to be scientistic" (p. 153). Empirical studies also show that this view of a science without limits is frequent among students. An example of this may be seen in studies of upper secondary students who state that science claims to be able to answer all questions (Hansson and Redfors 2007a, 2007b; Hansson and Lindahl 2010). Thus, there is an urgent need for the teaching of science starting to challenge views upon science related to scope and limits.

Nowadays many policy documents around the world explicitly state that, at least some aspects of, NOS should be part of compulsory science. Sometimes students should also learn about the limits of science. This is the case in the AAAS as well as the NGSS documents. Also in the Swedish context, the intention of the national curriculum developers is that the students should learn about the limits of science.

In this chapter, the limits of science are thought about as an important aspect of nature of science. One reason for this is that when *not* teaching about the limits of science, the hidden curriculum of scientism is likely to continue to be reproduced (Hansson 2018). The consequence of this is that science is distorted to many students who do not share naturalistic ways to view upon the world. Research has reported on students who associate science with scientism and atheism, but for whom such a science is hard to identify with and find meaningful (Hansson and Lindahl 2010). One example of a student associating science with very big claims is Camilla. She states that: “I don’t understand why one tries to understand something I think one will never do. Humans believe that she is capable of much more and is much more than she really is” (Hansson and Lindahl 2010). Addressing possible ways to view the scope and limits of science will more fully and more accurately describe science for all students.

An important task for teachers and researchers is to find ways to plan for a teaching that aims at discussions in science class on different ways to understand science, and thus break the science teaching traditions that often include a scientistic and atheistic hidden curriculum. Succeeding with this important task will make more students feel comfortable in science class and give more students possibilities to engage in science in ways meaningful for them. Below two examples of activities are suggested that could be used for teaching the limits of science. The activities could be used in secondary school, but also in teacher education and in-service teacher training.

34.2 Classroom Activities: Considering the Limits of Science

Here I describe two classroom activities designed to focus on, and invite students to discuss, the limits of science. Both activities are card-sorting activities that are preferably worked with in small student groups, after an introduction by the teacher. Students’ work with the activities should be followed by a teacher-led discussion taking the starting point in the students’ discussions. During this discussion, the teacher should problematize taken-for-granted views and describe different possible viewpoints. The teacher also has the possibility to communicate to the students that on many of these NOS-related issues there are different viewpoints among, e.g. scientists, philosophers of science, sociologists and historians.

Both activities have been used with pre- and in-service teachers. They have also in different ways been used with secondary students. Here a description of the activities is provided along with experiences from implementing them. Also possible discussion points and themes possible for the teacher to highlight during the discussions are suggested.

34.2.1 Activity 1: What Characterizes Scientifically Appropriate Questions?

The first activity consists of a number of questions to be sorted by the students based on whether the different questions are scientific or not. The activity builds on the view that science has limits and that, for example, policy, value, ethical and religious questions are outside the scope of science (see above). Thus, the activity is designed to give students possibilities to discuss what characterize questions that can be worked with scientifically. The activity is possible to use without students having any specific previous training, as a starting point for further discussions. The activity is inspired by a study by Driver et al. (1996) in which pair interviews were performed with the starting point in students' views concerning whether 11 different questions constituted scientific questions or not and what characteristics scientific questions have. In this chapter their idea has been developed in different ways, e.g. the set of questions have been exchanged and a wider range of questions are suggested.

The activity suggested includes 18 questions (see Table 34.1) written on cards (one question on each card). The set of questions covers *scientific* and also *socio-scientific* (Ratcliffe and Grace 2003) *(individual as well as collective decision making)*, *ethical*, *religious* and *aesthetical* questions. The categorization of questions as socio-scientific, ethical, religious and aesthetical are not important per se, and partly overlap, but could be a help for the teacher to focus upon partly different limits of science.

Thus students, through the activity, are invited to discuss the limits between science and religion, between science and ethics, between science and societal/socio-scientific issues and between science and aesthetics. Examples of questions suggested for the activity are: *Does life exist outside Earth? Should we use nuclear power? Can cell phones cause cancer? Should I buy eco-labelled bananas? Does a god exist? Is it wrong to show monkeys at zoo?* Thus, both questions most often viewed as outside and inside the scope of science are included. See Table 34.1 for all 18 questions (questions could of course be added or removed so that the set of questions suits the student group). The questions suggested for highlighting a specific limit constitute both questions usually viewed as scientific and non-scientific. For example, the questions suggested for discussions on the limit between science and ethics include both questions that are characterized by the need for value judgements concerned with right or wrong (e.g. Is it right to raise chickens in cages?) and questions that are possible to investigate scientifically (e.g. How do chickens raised in cages feel?).

The questions suggested as "Scientific" in Table 34.1 are all questions that could somehow be empirically investigated. This could be a fruitful starting point for students to come to grips with what characterizes scientific questions. The empirical basis for science is also an aspect normally suggested for NOS teaching in compulsory school. It is however possible to develop the activity further and include also, for example, more theoretically oriented questions to expand further on the image of science.

Table 34.1 Questions that are to be sorted as *scientific* or *non-scientific* during the activity. One possible sorting is suggested here, with scientific questions indicated by an ∗

Questions inviting discussions on the limit between *science and religion*	Questions inviting discussions on the limit between *science and ethics*	Questions inviting discussions on the limit between *science and societal/ socio-scientific issues*	Questions inviting discussions on the limit between *science and general value-questions (aesthetics)*
Does a god exist?	Is it wrong to show monkeys at zoo?	Should we use nuclear power?	Is a yellow shirt looking better than a red one?
Is there life after death?	Is it right to raise chickens in cages? (new)	Should I buy eco-labelled bananas?	Which novel is best?
Does life exist outside Earth? (∗)	Is it right to export electronic waste to developing countries? (new)	How does radiation affect humans? (∗)	Is dog a better pet than a snake?
What characteristics do planets orbiting other stars have? (∗)	How do chickens raised in cages feel? (∗) (new)	Can cell phones cause cancer? (∗)	What characterizes dogs as a species? (∗) (new)
How old is the Earth? (∗)		Which viruses can spread from pets to humans? (∗)	

Questions that have not been tested in class, in secondary school or in pre/in-service teacher education are indicated by the word "new" after the question

One rather easily identified scientific question (*Which virus can spread from pets to humans?*) is included in the activity as a reference. Such a question normally does not cause any problems for teachers or students. In the same way also one, from the beginning, supposedly easily identified non-scientific question was included (*Is a yellow shirt looking better than a red one?*). This question is categorized above as an aesthetical question (see Table 34.1). However, during in-service teacher workshops, teachers have sometimes argued that argued that this question is a scientific one, putting forward biological arguments concerning as to why colours are perceived in different ways by humans. However, most teachers, according to my experience, recognize this question as a non-scientific one.

34.2.1.1 Specific Instructions for the Activity

Phase 1: Sorting the Questions (Group Work)

After a short introduction by the teacher on how the activity will be performed, students start on the activity. During the first phase, the students work in small groups. Each group gets a set of cards with all 18 questions written on them (one question on each card). The task is to sort these cards in respect of whether a specific question is a scientific one or not. It is of course also possible to adjust this step and let the students work in different constellations during the task. One example is two teachers who were introduced to the activity during in-service teacher training and after that tried the activity in their own classes. They describe how they when implementing the activity first let the students work on the sorting individually, after a while the discussions continued in pairs of students, and finally they formed larger student groups. These two teachers reported positive experiences from letting their students work in these different constellations (Sacic and Sahlström 2014).

Phase 2: Formulating Reasons for the Sorting (Group Work)

During the second phase, when the students have finished their sorting of the cards, the teacher asks: "What is it that makes you think that these questions are scientific?", and "What is it that makes you think that these questions are non-scientific?" This is a similar approach to what Driver et al. (1996) did during their interviews. The student groups can be asked to write down their reasons for their sorting and finally they can be challenged by the teacher to formulate their view on what makes a question scientific or non-scientific?

Phase 3: Whole Class Discussion

When the student groups have finished the second phase, the teacher invites students to take part in a whole class discussion on the topic. The student groups share their preliminary formulations of their views on what makes a question scientific or non-scientific, and the teacher leads a discussion about what characterizes their different formulations. The teachers' role is to moderate the discussions, highlight different positions, and if necessary add viewpoints and reasons for specific viewpoints. It is the teachers' responsibility to make sure different positions are scrutinized and to add viewpoints and reasons that are not put forward by the students. The teacher can also contribute with examples of how science has been defined and introduce students to the problems of finding suitable formal demarcation criteria for science (Curd et al. 2013; Turgut 2011).

34.2.1.2 Examples of Issues to Focus on During Whole Class Discussion

With the starting point in the activity, limits to societal, ethical, religious and aesthetics are addressed. For example, concerning the limit between science and societal issues, the activity makes discussions possible on, e.g. the difference between the question *"How does a nuclear power station work?"* (scientific question) and the question "*Should we stop using nuclear power?"* (societal/socio-scientific question). It is common that students spontaneously state that questions which include a scientifically related phenomenon or object (such as nuclear power) is sorted as scientific – thus they do not differ between the two types of questions. Another example of the latter type of question is *Should I buy eco-labelled bananas?* (see also Table 34.1). These questions are, in the science education literature, labelled socio-scientific issues (SSI). In the first case, the decision making is on the societal level, and in the second case, on the individual level. Socio-scientific issues have scientific dimensions, but could not be decided upon only on scientific grounds (e.g. Ratcliffe and Grace 2003). Instead the scientific aspects of the questions have to be weighed together with ethical and economical aspects. For example, the issue of whether we should use nuclear power has not only scientific dimensions but also economical and ethical dimensions. Different aspects have to be weighed against each other, and the decision or point of view on the issue is value based. See also Stenmark (2008) for philosophical perspectives on the contribution and limitations of science in relation to policy and value issues.

From the starting point of the activity, you can also discuss, e.g. whether science has anything to say on religious issues and where limits could be drawn. Such possibilities arise from sorting cards such as *"Does a god exist?", "How old is the Earth?"* or *"Does life exist outside Earth?"* (Table 34.1). When discussing questions such as "Does a god exist?", my experience is that scientistic views often come to the forefront. This happens when the students state that science has no real limits to religious issues. Instead science is viewed to be associated with scientism and atheism. Conflict images as well as "God-of-the-gaps[1]" images (Barbour 2000) of the relation between science and religion are frequent. Thus, the activity invites students and teachers to discuss the relationship between science and religion and the relationship between science and scientism. Teachers need to be prepared to add possible standpoints, such that scientism is possible to combine with science but that other worldviews and ideologies are also possible to combine with science (Cobern 2000a; Taber 2013; Hansson and Lindahl 2010). This is important because Hansson and Redfors (2007b) show that it could be hard for students to formulate arguments against an equal sign between science and scientism. The experience from in-service teacher training shows that this could be hard also for science teachers.

Other questions suggested in this activity make it possible to discuss how limits for science could change. For example, in the past, the issue of whether life exists beyond Earth was more or less a philosophical question, while today a whole research area – astrobiology – basically is engaged in this profound question (Des Marais et al. 2008). Discussing a new research field such as astrobiology also makes it possible to discuss how new – and in this case, interdisciplinary – research fields can emerge. This is an example of how it is possible to, with the starting point in discussions of the limits of science, in the spur of the moment take the possibility to discuss other NOS aspects as well (see also Hansson and Leden (2016)).

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[1] According to a "God-of-the-gaps" reasoning the role for a god gets smaller and smaller as science proceeds.

The above described activity has been demonstrated and used during many pre- and in-service teacher trainings, and it has been reported, by secondary teachers, to work well in lower secondary science too (Sacic and Sahlström 2014).

34.2.2 Activity 2: On What Presuppositions Is Science Based?

The second activity is also a card-sorting activity. This activity was originally developed and used in a research project (Hansson and Redfors 2007b) after inspiration from the card exchange game in Cobern and Loving (2000) (see also Chap. 11 in this book) – but with another focus of the content of the cards, as well as another design of the activity. After that, variants of the activity have been used by this author in numerous in-service and pre-service teacher education courses and also in lower and upper secondary classes as part of an EU project (Hansson et al. 2011). A variant has also been used in an interview research study (Hansson and Lindahl 2010). Here a description of the activity will follow, together with experiences from the implementations.

The activity takes as a starting point of a notion that science builds upon presuppositions (Cobern 1991). Examples of such presuppositions are as follows: the world is ordered, comprehensible and uniform[2] (Aikenhead and Ogawa 2007; Poole 1998). However, it is frequent that students do not know about these starting points for science (Hansson 2014). In addition, it is also frequent that students associate science with other presuppositions which are not necessary for science – for example, presuppositions associated with atheism and scientism. These presuppositions are however not necessary for science (Cobern 2000a; Hansson 2018). The aim of the activity is that students should get knowledge about the kind of presuppositions that science builds upon, as well as that presuppositions associated with atheism and scientism do not constitute such necessary presuppositions for science. Thus, the activity highlights the limits between science and religion and science and scientism.

In the activity, statements are written on cards. Included are statements that, according to the theoretical starting point discussed above, constitute necessary presuppositions for science (Cobern 1996; Hansson 2014) (e.g. *There are patterns/order in the universe*), scientistic statements (Stenmark 2001; Poole 1998) (e.g. *Everything has/will have a scientific explanation*) and religious statements (e.g. *A god has created the universe*). See Table 34.2 for more examples of statements.

These statements are to be sorted by the students under one of the three headings:

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[2] Not everyone agrees that science has presuppositions (Gauch 2003). From the starting point in positivism or strict empiricism, science lacks presuppositions. This is also the view held by many scientists (Gauch 2003; Margenau 1950). However, this view has been questioned in philosophical as well as cultural studies of science (see Hansson 2014). Discussions on different views upon this could be part of the teaching activity.

Table 34.2 Statement to be sorted with the starting point, whether they are necessary starting points for science or not. The statements have previously been presented in (Hansson and Redfors 2007b), where the choice of these specific statements was argued for

Necessary starting points for science (presuppositions made by science)	Religious statements	Scientistic statements
There are patterns/order in the universe	A god or supreme power exists	Everything has or will have a scientific explanation
There are patterns/orders in the universe that wholly or partially can be discovered and understood by humans	There is no god or supreme power	There are things that never will be possible to describe scientifically
The universe is incomprehensible for humans	A god has created the universe	Things that cannot be proven or explained do not exist
All places and events in the universe are unique and because of that impossible to describe with the same models	A god or supreme power can influence the development of the universe	One should not believe in things that are not proven
The physical laws that are valid here are valid also in every other place in the universe	A god or supreme power can intervene here on earth, for example, through performing miracles or wonders	Only science can tell us what is really true about the world
The physical laws have always been valid, that is, they were valid all along the history of the universe		

- *Science builds upon this*
- *Science contradicts this/builds upon the opposite*
- *Science neither builds on nor contradicts this*

34.2.2.1 Specific Instructions for the Activity

Phase 1: Sorting of Cards (Group Work)

The activity starts with a short introduction by the teacher who describes the task and the meaning of the different headings. Under the first heading “Science builds upon this”, students will be asked to include only statements that describe necessary starting points (presuppositions) for science. Under the second heading “Science contradicts this”, statements for which science builds upon the opposite are to be placed, and under the third heading, statements describing a viewpoint on which science has nothing to say (science does not contradict the statement, but does not build on it either). It is important that the teacher emphasizes that the ground for the sorting should not be whether the students themselves agree with the statement or not, but instead the relation between science and the statements. When this has been clarified, the students could start their work on sorting the cards.

Preferably, the students will work on this task in small groups. Students sort the cards with the statements together in the small groups. During their work, they are challenged by the teacher to formulate reasons for their sorting. The activity normally raises many discussions about what science builds (and not builds) upon, as well as on the limits of science. Most often different viewpoints are present in the groups, but it could be hard for the students to come up with good reasons for why they sorted a statement into a particular group. It can also be necessary for the teacher to remind students of the meaning of the headings under which the statements are sorted and perhaps ask students questions such as *Is this something that really is a necessary starting point for science, something science cannot live without? Or could scientists have different opinions?*

Phase 2: Whole Class Discussion

Finally, the teacher arranges a follow-up whole class, teacher-led, discussion. The groups could share with other students which statements they view as necessary for science and which were contradicted by science and describe reasons for their sorting. When comparisons between groups are made, it could be good to remind students of the meaning of the headings under which the statements are sorted and perhaps (again) ask students questions such as *Is this something that really is a necessary starting point for science, something science cannot live without? Or could scientists have different opinions?* Teachers need also to be prepared to add arguments and/or ways of sorting the cards, if necessary. For example, as described in Hansson and Redfors (2007b), students in the small group discussion phase had problems formulating arguments for the viewpoint that scientistic statements were not necessarily a starting point for science. Similar presuppositions could be compared and grouped together.

34.2.2.2 Examples of Issues to Focus on During Whole Class Discussion

During whole class discussion, the teacher could introduce scientism, as one worldview that can, but not has to, be combined with science. Also in pre- and in-service teacher training, it could sometimes be necessary for the instructor to add viewpoints and/or arguments and discuss different ways to view science. Some issues could be especially tricky, for example, the statement about miracles. Different viewpoints exist on whether miracles are compatible with science or not – depending on, for example, how scientific laws are viewed (e.g. Poole 1998). This constitutes one of many examples of how the relationship between science and religion depends on how religion is understood, but also on how nature of science is viewed upon (Reiss 2008). In connection with discussions on the relationship between science and religion, it is also possible to discuss example of historical scientists as well as scientists living today, who are atheists as well as those who have a religious faith. In this way, it is illustrated in an additional way that not only one worldview is compatible with science (Cobern 2000a, b).

Also, most often in my experience, there is a need to discuss the presuppositions upon which science is built, which most often are taken for granted in science and in the teaching of science (Cobern 2000a; Hansson 2014). This could be done with the starting point in the students sorting of the cards. The teacher can share examples of how presuppositions of order, comprehensibility and uniformity are used in science.

However, these presuppositions are not taken for granted by upper secondary students (Cobern 2000b; Hansson 2014), and from my experience with pre- and in-service teachers, there is often a need to discuss that science builds upon order, uniformity and comprehensibility. Especially the statement about the validity of the laws over space most often raises discussions. Concerning this it could be necessary for the teacher to add arguments about the importance of the presupposition of uniformity (also in the universe) for the possibility to construct scientific models describing, e.g. the development of the universe or the life cycles of the stars. In these cases, scientists presuppose uniformity, that is, nature behaves the same at all places and in all times. For example, the spectra from a specific atom does not change, but looks the same independently if the atom is in a star or on Earth (Hansson 2014; Hansson and Redfors 2007b).

The activity has the potential to lift discussions about the relationship between science and religion, or between science and scientism, away from specific content areas (e.g. the theory of evolution or the Big Bang theory). Instead the limits of science are addressed as part of NOS, through a discussion on what kind of presuppositions are necessary for science. This could be a relief for students. Discussing what kind of presuppositions are inherent in science, and what kind of presuppositions that are not necessary but are used by some people to understand science through, could be a way to understand why people do not always agree on, for example, relationships and limits between science and religion. These discussions often lead to other NOS aspects being raised and discussed, such as the empirical knowledge base and human aspects of science. Also possible here is to raise discussions not only on this limit, but draw parallels to other limits such as the limit between science and ideology. For example, are technological optimistic and modernist ideological viewpoints necessary starting points for science? Or is it possible to engage in science from the starting point in other ideological viewpoints?

34.3 Concluding Remarks

In this chapter, two suggestions of teaching activities have been described, both aiming at discussions of the limits of science. That science has no real limits have been described as a common myth about science (McComas 1998). For example, I and my colleagues (Hansson and Lindahl 2010, Hansson and Lindahl 2015; Hansson and Redfors 2007a, b) have shown how scientism and atheism are frequently associated with science by upper secondary students. This shows that the notion of a science with no limits is still not problematized in the science classrooms. Instead it could be argued that such views are part of a hidden curriculum in many science classes (Hansson 2018). Including the kind of activities and discussions suggested here is one way to start problematizing the equal sign between science and scientism (including atheistic views). Explicitly discussing this makes it easier for students and teachers to notice scientistic and atheistic companion meanings (Roberts 1998) in the classroom, textbook or media. That students become aware of that science is viewed, by most scientists and philosophers to have limits, and that different worldviews (not only scientism but also different kinds of religious worldviews) are compatible with science has the potential to open up science for more students. The teaching of science as well as science itself could in this way become meaningful for more students.

References

Aikenhead, G. S. (2006). *Science education for everyday life: Evidence-based practice*. New York: Teachers College Press.

Aikenhead, G., & Ogawa, M. (2007). Indigenous knowledge and science revisited. *Cultural Studies of Science Education, 2*(3), 539–620.

Barbour, I. G. (2000). *When science meets religion* (1st ed.). San Francisco: Harper San Francisco.

Cobern, W. W. (1991). *World view theory and science education research. NARST Monograph No. 3*. Manhattan: National Association for Research in Science Teaching.

Cobern, W. W. (2000a). The nature of science and the role of knowledge and belief. *Science & Education, 9*, 219–246.

Cobern, W. W. (1996). Worldview theory and conceptual change in science education. *Science Education, 80*(5), 579–610.

Cobern, W. W. (2000b). *Everyday thoughts about nature*. Dordrecht: Kluwer Academic Publishers.

Cobern, W. W., & Loving, C. C. (2000). The card exchange: introducing the philosophy of science. In W. F. McComas (Ed.), *The nature of science in science education. Rationales and strategies* (pp. 73–82). Dordrecht: Kluwer Academic Publishers.

Curd, M., Cover, J. A., & Pincock, C. (2013). *Philosophy of science: the central issues* (2nd ed.). New York: W.W. Norton.

Dawkins, R. (2006). *The God delusion*. Boston: Houghton Mifflin Co..

Des Marais, D. J., et al. (2008). The NASA astrobiology roadmap. *Astrobiology, 8*(4), 715–730.

Driver, R., Leach, J., Millar, R. & Scott, P. (1996). *Young people's images of science*. Bristol: Open University Press.

Gauch, H. G. (2003). *Scientific method in practice*. Cambridge: Cambridge University Press.

Hansson, L. (2014). Students' views concerning worldview presuppositions underpinning science: is the world really ordered, uniform, and comprehensible? *Science Education, 98*(5), 743–765.

Hansson, L. (2018). Science education, indoctrination, and the hidden curriculum. In M. R. Matthews (Ed.), *New perspectives in history, philosophy and science teaching research*. Dordrecht: Springer.

Hansson, L., & Leden, L. (2016). Working with the nature of science in physics class: turning "ordinary" classroom situations into nature of science learning situations. *Physics Education, 51*(5), 055001.

Hansson, L., & Lindahl, B. (2010). "I have chosen another way of thinking" Students' relations to science with a focus on worldview. *Science & Education, 19*, 895–918.

Hansson, L., & Lindahl, B. (2015). Students, science and scientism: A story about resistance. In *Proceedings from the IHPST Thirteenth Biennial International Conference*, Rio de Janeiro, July 22–25, 2015. http://ihpst.net/content.aspx?page_id=22&club_id=360747&module_id=187166

Hansson, L., & Redfors, A. (2007a). Physics and the possibility of a religious view of the universe: Swedish upper secondary students' views. *Science & Education, 16*, 461–478.

Hansson, L., & Redfors, A. (2007b). Upper secondary students in group discussions about physics and our presuppositions of the world. *Science & Education, 16*, 1007–1025.

Hansson, L., Redfors, A., & Rosberg, M. (2011). Students' socio-scientific reasoning in an astrobiological context – The design and implementation of a digital learning environment. *Journal of Science Education & Technology, 20*, 388–402.

Margenau, H. (1950). *The nature of physical reality. A philosophy of modern physics*. New York: McGraw-Hill.

McComas, W. F. (1998). The principal elements of the nature of science: dispelling the myths. In W. F. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 53–70). Dordrecht: Kluwer.

Medawar, P. B. (1984). *The limits of science* (1st ed.). New York: Harper & Row.

Poole, M. (1995). *Beliefs and values in science education*. Berkshire: McGraw-Hill Education.

Poole, M. W. (1998). Science and science education: A Judeo-Christian perspective. In W. W. Cobern (Ed.), *Socio-cultural perspectives on science education. An international dialogue* (pp. 181–201). Dordrecht: Kluwer Academic Publishers.

Ratcliffe, M., & Grace, M. (2003). *Science education for citizenship. Teaching socio-scientific issues*. Philadelphia: Open University Press.

Reiss, M. J. (2008). Should science educators deal with the science/religion issue? *Studies in Science Education, 44*(2), 157–186.

Roberts, D. A. (1998). Analysing school science courses: The concept of companion meaning. In I. D. A. Roberts & L. Östman (Eds.), *Problems of meaning in science curriculum* (pp. 5–12). New York: Teacher College Press.

Sacic, J., & Sahlström, A. (2014). Naturvetenskaplig eller icke-naturvetenskaplig fråga. [Scientific or non-scientific question]. *LMNT-nytt*, 2014:2.

Stenmark, M. (2001). *Scientism: Science, ethics and religion*. Aldershot: Ashgate Science and Religion Series.

Stenmark, M. (2008). Science and the limits of knowledge. In *Clashes of knowledge* (pp. 111–120). Dordrecht: Springer.

Stenmark, M. (2017). *Environmental ethics and policy-making*. London: Routledge.

Taber, K.S. (2013). Conceptual frameworks, metaphysical commitments and worldviews: The challenge of reflecting the relationships between science and religion in science education. In N. R. Mansour & Wegerif (Eds.), *Science education for diversity theory and practice*. Springer.

Turgut, H. (2011). The context of demarcation in nature of science teaching: The case of astrology. *Science & Education, 20*(5–6), 491–515.

Chapter 35
Supporting Science Teachers' Nature of Science Understandings Through a Specially Developed Philosophy of Science Course

Kostas Kampourakis

35.1 Introduction

There is a widespread agreement among science educators and science standards in various countries that science teaching in schools should not be limited to content knowledge only, but that it should also include aspects of nature of science (NOS). However, it has been found that, despite the significant efforts in this direction, science teachers face difficulties in effectively teaching NOS (e.g., Bartos and Lederman 2014; Capps and Crawford 2013; Herman et al. 2013). Therefore, the preparation of teachers themselves is necessary so that they may be able to effectively teach relevant NOS aspects. In this chapter, I argue that this is where an understanding of philosophy of science has a critical role to play. Previous research with preservice teachers has supported the conclusion that an explicit philosophy of science course can help teachers develop deep and coherent understandings of nature of science (e.g., Abd-El-Khalick 2005). Philosophy of science can inform science education research and practice in many ways, such as by clarifying the meaning of unique concepts or the processes of scientific inquiry and explanation. Consequently, it is important that teachers understand the relevant philosophical topics well.

However, this is not easy as philosophy of science is conceptually demanding and its study requires significant effort and investment of time. Even in the case of philosophy of science books written for science teachers and educators (such as Kampourakis 2013a), problems may still exist even when instructors actually use such books. For instance, in the case where such a book was used in a philosophy of

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_35

biology course for biology undergraduates, even though the chapters were found to be readable and understandable, the terminology and some complex and challenging concepts and arguments were problematic and made a thorough understanding occasionally difficult to achieve (El-Hani 2014). Of course, few science teachers will have had such a class, and fewer still are likely to seek out information on their own about this topic. Therefore, we all must work together to improve science teachers' understanding of NOS, and a well-designed philosophy of science courses could serve such a purpose. However, science educators should explicitly connect any reference to philosophy of science to NOS aspects and ideas that teachers can understand and use. This suggestion is not a simplification or refinement of philosophy of science, but rather a careful introduction of its topics in the context of science education, in a pragmatic and explicit manner.

35.2 Philosophy of Science and Nature of Science

Philosophy of science emerged as a field of study during the nineteenth and the twentieth centuries, when science became distinct from natural philosophy and natural history. Although the main preoccupations of philosophers of science have changed over the centuries, some questions such as those about causality have always been under focus. What is important is that thinking philosophically about science has always been useful and relevant to the conduct of science. Science is often described as a quest for knowledge about the natural world. In turn, philosophy of science aims to clarify what it means to "know" in science, what distinguishes knowledge from belief, which are the main characteristics of scientific knowledge, why scientific knowledge is tentative and to what extent, or whether this feature undermines its reliability. Philosophy of science also clarifies the structure and nature of scientific explanations, the role of causality therein, or how scientists decide to favor one among several competing explanations.

A major characteristic of science is that it is empirical in nature, and so scientific knowledge and explanations are derived from empirical data, which stand as evidence for accepting or rejecting particular scientific theories. Another focus of philosophy of science relates to the structure of scientific theories, how they are developed and tested, what they consist of (models, principles, etc.), how they change over time, what are the virtues of a good scientific theory, what is the role of representation in scientific theorizing, what is the role of experiments in testing scientific hypotheses and theories, and more. Finally, philosophy of science studies the characteristics of the social process in science (debates, peer review, etc.), as well as the implications of scientific knowledge for society and how the practice of science is influenced by society (for these topics and more, see Godfrey Smith 2003; Rosenberg 2005; Barker and Kitcher 2013; Curd and Psillos 2013).

These and other topics studied by philosophy of science make it directly relevant to teaching about NOS. Especially for teaching science, particular topics have a special relevance: understanding science as a cognitive activity, its aims and methods, what makes science a rational activity, what drives theory change in science, how scientific theories relate to the natural world, how scientific concepts are formed, and more. However, often teachers' undergraduate training does not include such topics. Furthermore, many of them do not usually have a first-hand experience of doing science and becoming more familiar with related issues. Therefore, it is important that teachers not only become familiar with these topics, but also explicitly relate them to their own teaching of science. This is mainly what NOS teaching is about. However, on the one hand, teachers cannot and should not become philosophers of science. On the other hand, they need to find ways to teach about NOS that they can really handle effectively. The most widely used approach so far to teach and assess NOS has been based on teaching some of the general NOS aspects (McComas 1998; Lederman et al. 2002; Osborne et al. 2003; Niaz 2009). These aspects have been found to be teachable and comprehensible. Elsewhere, I have argued that it is these general NOS aspects that science teaching should first explicitly address. Once this is achieved, students could be further taught about the values, the institutions, and other features of science (Kampourakis 2016).

35.3 A Philosophy of Science Course for Science Teachers

Based on these considerations, I developed a philosophy of science course specifically for science teachers, which included sophisticated philosophy of science explicitly linked to general NOS aspects (Table 35.1). These are general aspects of the nature of scientific inquiry (NOSI) and nature of scientific knowledge (NOSK). The distinction between the NOSI and NOSK aspects is based on pragmatic, not normative, criteria, as it has been found that students' views about NOSI can change without similar changes in their views of NOSK. For example, in a study with elementary students, it was found that those who were taught about NOS implicitly did not substantially improve their NOS understandings. This also shows that engaging in inquiry and learning about science process skills are not equivalent to learning about NOS in general or NOSK in particular (Khishfe and Abd-El-Khalick 2002). Of course, the course could be redesigned to draw upon any of the collections of general NOS aspects and of course include any other aspect that might be considered relevant.

The course (Philosophy of Science: Key Topics and Applications to K-12 Science Education, Illinois Institute of Technology) was offered online and consisted of 11 weekly classes of 150 min each and included two microteaching sessions of the same duration during which the participating teachers presented how they would

Table 35.1 The general aspects of NOSI and NOSK on which the present study focused (Lederman 2007)

Aspects of nature of scientific inquiry (NOSI)	Aspects of nature of scientific knowledge (NOSK)
1. Scientific investigations all begin with a question, but do not necessarily test a hypothesis	1. Observation and inference are different
2. There is no single set and sequence of steps followed in all scientific investigations (i.e., no single scientific method)	2. Scientific laws and theories are distinct forms of knowledge
3. Inquiry procedures are guided by the question asked	3. Scientific knowledge is empirical, as it is based on and/or derived from observations of the natural world
4. All scientists performing the same procedures might not get the same results	4. Scientific knowledge involves imagination and creativity
5. Inquiry procedures can influence the results	5. Scientific knowledge is subjective
6. Research conclusions must be consistent with the data collected	6. Scientific knowledge is influenced by the cultural contexts in which it is developed
7. Scientific data are not the same as scientific evidence	7. Scientific knowledge is never absolute or certain but tentative and subject to change
8. Explanations are developed from a combination of collected data and what is already known	

make use of philosophy of science to teach about NOSK and NOSI in their own classes. I taught using PowerPoint slides which were distributed to participants after each class. The teaching format that I followed was based on a modular structure. Each module included a short presentation of a topic that I made, which was followed by a question posed to participants and subsequent discussion. At the end of each class, I gave written assignments and suggested readings to participants. Electronic versions (PDF files) of the suggested readings were provided to participants via an institutional platform prepared for this purpose. I also provided relevant examples of topics that might be included in the microteaching sessions of the course. From all the examples that I provided during the course, teachers were asked to select one and prepare a lesson plan and a presentation for the microteaching session. The NOSI and NOSK aspects of Table 35.2 were taught explicitly and reflectively and were related to key philosophy of science topics. Whenever a related topic was presented, the respective NOSI or NOSK aspect was emphasized. The participants were motivated to think about these aspects, as well as to consider how they might use the topics, concepts, stories, and examples presented to inform their own teaching.

Table 35.2 The topic of and the NOSK/SI aspects explicitly discussed in each class of the course (see also Table 35.1)

Class	Topic	NOSK/SI aspects explicitly discussed
1.	The relevance of philosophy of science to science instruction	
2.	Key concepts in philosophy of science	
3.	Science and epistemology	NOSK1, NOSK3, NOSK4, NOSK5, NOSK7
4.	Causation and explanation	SI8, NOSK2
5.	Scientific evidence and theorizing	SI6, SI7, NOSK2, NOSK3, NOSK5, NOSK7
6.	Scientific realism/models/representation	NOSK1, NOSK4, NOSK5, NOSK6, NOSK7
7.	Methodological and epistemic characteristics of experimental science	SI1, SI2, SI3, SI4, SI5, SI6, SI7, SI8
8.	Methodological and epistemic characteristics of historical science	SI1, SI2, SI3, SI4, SI5, SI6, SI7, SI8
9.	Conceptual change in science	NOSK1, NOSK3, NOSK4, NOSK5, NOSK6, NOSK7
10.	Science and ethics/science and religion	NOSK6
11.	Philosophy of science and history of science	NOSK1, NOSK2, NOSK3, NOSK4, NOSK5, NOSK6, NOSK7
12.	Microteaching session	
13.	Microteaching session	

35.3.1 Class 1: The Relevance of Philosophy of Science to Science Instruction

The first class served as an introduction to teaching about NOSK and NOSI. The explicit/reflective approach to teaching about NOS and its use were presented to participants, noting that this would be the approach implemented in their philosophy of science course. Then, the criticisms of this approach were presented and discussed in detail. The points explained to teachers were that (1) whatever is taught at schools has previously undergone some kind of didactic transposition (not just simplification) in order to align with the pedagogical goals; (2) the main aim of the "general NOS aspects" conceptualization was to address students' preconceptions about NOS by discussing some aspects common across all science, not to give them criteria for demarcating science from non-science; (3) it seems unclear how (2) can be achieved if NOS teaching begins from the specifics of the various science disciplines and their differences, instead of general aspects that can then be elaborated upon with reference to specific disciplines; and (4) it is pedagogically useful to distinguish between aspects of NOSK and aspects of NOSI because students have been found to conceptualize them independently (see Kampourakis 2016).

Finally, I used the concept of biological adaptation as a concrete example of how philosophy of science can be used to inform science teaching was discussed, based on Kampourakis (2013b). This is a concept with which all teachers were generally familiar. After presenting how adaptation is defined in the philosophy of science and what the major differences among the various definitions of adaptation are, I presented how adaptation is defined in textbooks. I noted several inconsistencies even with different definitions in the same textbook, without any explanation of the underlying differences. Overall, several types of definitions existed: (1) definitions of adaptation as a process; (2) historical definitions of adaptation as a trait, i.e., ones that described adaptation as the outcome of natural selection; and (3) ahistorical definitions of adaptation as a trait, i.e., ones that described adaptation as a trait that provides an advantage to its bearers. Leaving the process definition aside, the historical definition overlooks the current contribution, and the ahistorical definition overlooks the historical process that brought it about. Given these, teachers reflected on what should they consider when teaching about adaptation. Participants reached the conclusion that students' preconceptions should be accounted for. Therefore, a definition of adaptation that would be used in education should incorporate both the historical and the ahistorical definition of adaptation as a trait, i.e., both the evolutionary history of the trait and its current significance to its bearers. Doing only the latter would deprive teachers from a tool, the historical process of how an adaptation emerged, which would be important to address students' misconceptions about purpose and design in nature. This was also an explicit example of how philosophy of science provides conceptual tools for teaching.

The suggestion made in this first class for the microteaching was for teachers to select a scientific concept such as "adaptation" (e.g., gene, force, atom, tectonic plate) and study the philosophy of science literature to see how the concept is defined there. I told participants that in case they decided to do this, I would provide them with some readings representative of the relevant literature. Then, they might compare this definition to those found in K–12 textbooks. Based on these, teachers were asked to present how they would teach about this concept in their classes, in a philosophically informed manner. The assignment was for teachers to write an essay to explain whether the criticisms of the "consensus approach" to teaching NOS were (a) well-founded and (b) relevant to the aims of K–12 science instruction. To answer these questions, teachers were asked to read and carefully consider the excerpts from critics that were presented during the class and that were included in my PowerPoint slides.

35.3.2 Class 2: Key Concepts in Philosophy of Science

This class featured a presentation and discussion of some key concepts in the philosophy of science, based on Psillos (2007) and French and Saatsi (2011) (concepts such as theory, evidence, confirmation, explanation, causation, laws, knowledge, scientific method, induction, deduction, abduction and inference to the best explanation, necessary and sufficient conditions, empiricism, unobservable entities, realism/antirealism, and underdetermination). This list included concepts that I thought that teachers should be aware of, but not ones that they would necessarily have to teach about. These are concepts that are generally used in philosophical parlance, and so I decided that teachers would benefit by being familiar with them. We devoted time to comparing the meaning of some of these terms to their vernacular use (e.g., compare the scientific concept of "theory" with how it is used outside science).

The suggestion made for the microteaching session was to prepare a lesson to show how participants would teach about what science is and how it is done, while explaining whether and how they would rely on philosophy of science for definitions of concepts such as evidence, theory, confirmation, etc. The assignment given was for teachers to explain how McComas (1998) and expanded in Chap. 3 of this volume relied on philosophy of science to describe the principal elements of NOS, as well as which element(s) is/are the most clearly explained and which is/are the most philosophically informed. Teachers were asked which two key concepts from philosophy of science from French and Saatsi (2011) they would definitely use and which two concepts they would never use in a class on Nature of Science (and why).

35.3.3 Class 3: Science and Epistemology

During the third session, we discussed the relation between science and epistemology in the context of what constitutes scientific knowledge. We had discussions about knowledge and belief, knowledge and truth, the grounding of scientific knowledge, the relation between observation and inference, and how scientific knowledge is acquired. Several cases from history of science were used to illustrate the main points.

For instance, to show that what scientists consider as true at some point may later prove to be false, I used the example of spontaneous generation. Until the mid-nineteenth century, scientists accepted spontaneous generation of life as a fact, until Louis Pasteur convincingly showed that life does not emerge from non-living matter. Another example to illustrate the same point was Copernicus' proposal of a heliocentric (sun-centered) model, instead of a geocentric (earth-centered) one.

To explain the inductive grounding of scientific knowledge, I explained how the knowledge that DNA is the genetic material in cells is grounded on the observation that all cells that scientists have studied have DNA as genetic material. Another example was to show that the knowledge that all organisms have common ancestors is grounded on the observation that all organisms that we have studied consist of cells, have DNA as genetic material, and have the same transcriptional/translational machinery, which (along with other) common characteristics are best explained by common ancestry.

Then I showed that scientific knowledge does not automatically arise as we observe the world, but that we must first ask questions about the world which direct our inquiry in the context of background knowledge. The first example used was that different questions, such as why organisms are adapted to their environments (asked by Charles Darwin among others) and why organisms exhibit significant similarities in their structure (asked by Geoffroy Saint-Hilaire among others), paved the way for figuring out that organisms have evolved through natural selection from common ancestors. Another example was that of Alfred Wegener who developed and tested the hypothesis of continental drift in order to explain the apparent fit between the coastlines of Africa and South America.

Then I discussed in detail the view that scientific theories are human inventions, by discussing with teachers the following quotation from Giere 2006:

> The inescapable, even if banal, fact is that scientific instruments and theories are human creations. We simply cannot transcend our human perspective, however much some may aspire to a God's eye view of the universe. Of course, no one denies that doing science is a human activity. What needs to be shown in detail is how the actual practice of science limits the claims scientists can legitimately make about the universe […] A proper understanding of the nature of scientific investigation supports the rejection of all claims to absolute truths. The proper stance, I maintain, is a methodological naturalism that supports scientific investigation as indeed the best means humans have devised for understanding both the natural world and themselves as part of that world. That, I think, is a more secure ground on which to combat all pretenses to absolute knowledge, including those based on religion, political theory, or, in some cases, science itself.

The class concluded with a discussion of methodological and metaphysical naturalism. Methodological naturalism asserts that science is a study of natural (as opposed to supernatural) phenomena only, supports its claims with empirically accessible evidence, and explains by appeal to material causes. Science does not and cannot say that there are no supernatural phenomena (such as the presence of a deity); it merely asserts that science does not and cannot study the supernatural. For this reason, methodological naturalism should be distinguished from metaphysical naturalism. The latter asserts that material natural phenomena studied by science are all that exist and denies the existence of supernatural entities or phenomena.

The suggestion made for the microteaching session was for teachers to show how they would teach that scientific knowledge is tentative, empirical, inferential, and subjective and that it involves human imagination and creativity, suggesting Giere (2006) and Audi (2011), excerpts from which were discussed during the class, as useful sources. Teachers were also asked to write an essay, as a home assignment, to answer the following question: "If what we consider as true is subject to change and if scientific knowledge is subjective and the product of human imagination and creativity, how reliable is scientific knowledge?"

35.3.4 Class 4: Causation and Explanation

The next class focused on causation and explanation. First, I noted that the general agreement among philosophers of science is that scientific explanations are usually causal. After the different theories of causation were briefly presented, I noted that an important common point in all of them is that causes are difference-makers for their effects. This means that causes do not exclusively produce their effects. Rather, a difference in a cause may produce a difference in some given effect. For instance, a match is not the only cause of a fire (oxygen and combustible materials are also causally relevant), but the difference in the status of the match (unlighted → lighted) can make the difference on whether fire will occur (fire will not occur by an unlighted match but can occur with a lighted one). Then we discussed the structure of scientific explanations, and the various accounts of scientific explanation from the philosophy of science were presented. Emphasis was put on "Inference to the Best Explanation" as an approach to form explanations that is commonly employed by scientists. According to this approach, there usually are several competing explanations for the same data, and scientists usually select the one that, if true, would best explain the available data. I suggested that teachers read Hitchcock (2008), Lipton (2008), Woodward (2008), and Brigandt (2013).

I suggested that a microteaching session possibility was for the teachers to show how they would teach about the nature and structure of scientific explanations, with a focus on a specific subject matter. For the assignment, teachers were asked to select a scientific explanation on a topic they were very familiar with and (a) identify the causes of the explanandum effect, (b) analyze the structure of the explanation and explain how it relates to the major accounts of scientific explanation from philosophy of science, and (c) compare this explanation to older competing ones and describe how IBE was/could have been applied.

35.3.5 Class 5: Scientific Evidence and Theorizing

The focus of the fifth class was on scientific evidence and theorizing. The discussion started with a case study from the history of science, with the experiments of Heinrich Hertz and Joseph John Thomson on cathode rays. This example provided a useful topic for discussion about the nature of scientific evidence. The conclusion we reached, based on Achinstein (2008), was that there are different kinds of evidence. In seeking evidence for a hypothesis, if a scientist is attempting to provide a good reason to believe it, requiring its truth, and if this does not vary between different epistemic situations, then what the scientist seeks is veridical evidence. However, when a scientist claims that some experimental result is evidence that a hypothesis is true, but we know or believe there is some flaw in the experiment, or if we have information not available to the scientist that casts doubt upon his hypothesis or refutes it, we can describe his experimental result as potential evidence, evidence for anyone in his epistemic situation, or his evidence, in the subjective sense (Achinstein 2008).

Then we turned the direction of the discussion to the topic of what constitutes a scientific theory. After discussing the syntactic and the semantic view of theories, a discussion followed that reached the conclusions that it is not possible to describe all theories with either the syntactic or the semantic view, as well as that there can be a hybrid view of theories. However, an important conclusion for educational purposes is that scientific theories are families of principles and models which can be used to describe and understand the natural world (implying acceptance of methodological naturalism). Finally, the virtues of a good scientific theory were discussed based on the work of McMullin (2008):

- Empirical fit → support by data
- Internal consistency → no contradictions
- Internal coherence → no additional assumptions
- Simplicity → testability and applicability
- External consistency → consonance with other theories
- Optimality → comparative success over other theories
- Fertility → novel predictions, anomalies, change
- Consilience → unification
- Durability → survival over tests
- Explanatory power

After the presentation of these characteristics, evolutionary theory was used as an exemplar for a good scientific theory to illustrate these virtues.

The suggestion for the microteaching session was for teachers to show how they would teach about the structure of scientific theories, with a focus on a specific subject matter, and how they would show how scientists rely on the available evidence to develop theories. Achinstein (2008) and McMullin (2008) were the suggested readings for this task. The assignment for teachers was to select a scientific theory they are very familiar with and analyze the kind of evidence that supports it and its virtues.

35.3.6 Class 6: Scientific Realism/Models/Representation

The sixth class focused on scientific models, representation, and realism and began with a discussion of the various kinds of models used in science and the features of those models. Then the idea of representing the natural world through models was discussed with a concrete example: geographical maps. Maps as representational tools have the following features that can be useful in teaching about models:

- They exhibit similarities with aspects of the real world (the distances on the map are equivalent to actual distances).
- They do not represent the earth, neither are they true of them (maps are much smaller and do not illustrate every possible detail).
- They are neither entirely precise nor entirely accurate (maps are two-dimensional whereas the world is three-dimensional).
- They are used for a specific purpose in a particular context (maps for navigating in the sea are different from geological maps).
- They are partial, as only some features of a territory are represented.
- They are similar to an area but not showing how it truly looks.

- They are of limited accuracy as, e.g., relative distances on the map do not correspond to relative differences on the ground.
- They are interest-relative, i.e., the features included in maps depend on the interests of their users.

Finally, we spent time on the issue of scientific realism and to the question whether science reveals how the natural world really is. For the microteaching session, teachers were encouraged to show how they would teach about the use of models in science, by relying on the history of science to show how particular models were developed and how these models have been modified since they were first proposed. Giere (2006) was the assigned reference for this topic, from which the idea of using maps as a concrete example of a model also came. Finally, for the home assignment, teachers were asked to select a model they are well familiar with and a) describe its strengths and its limitations and b) argue if the entities posited by the model truly exist or not.

35.3.7 Classes 7 and 8: Methodological and Epistemic Characteristics of Experimental and Historical Science

The methodological and epistemic characteristics of science were the focus of the next two classes, by explicitly distinguishing between experimental science and historical science. Methodological characteristics relate to the methods used by scientists (e.g., experiments, observations, etc.), whereas epistemic characteristics refer to the sources of knowledge and their own features (e.g., experimental evidence vs. historical evidence). After clarifying what an experiment is and what its characteristics are, based on Hacking (1983), discussion turned to the uses of experiments in science using concrete examples from the history of science, focusing on the history of biology and on classic experiments that are usually included in textbooks such as those conducted by Thomas Hunt Morgan, Hermann J. Muller, Marshall Nirenberg, Alfred Hershey, Barbara McClintock, and their colleagues in order to show that experiments can be used in order to confirm or refute hypotheses, select between competing hypotheses, obtain evidence to answer questions, raise novel questions, or provide evidence for the existence of unobservable entities. Emphasis was put on the fact that all the scientists mentioned were awarded a Nobel Prize, which for some people is a sign of the "superiority" of experimental science.

The microteaching suggestion stemming from Class 7 was for teachers to select a scientific experiment and describe the inquiry process that guided its design, as well its contribution to science (confirmation or refutation of a hypothesis, raising new questions, etc.). Besides Hacking (1983), suggested readings were Arabatzis (2008) and Franklin (2012). The home assignment was for teachers to select a scientific experiment they were well familiar with and a) describe the inquiry process that guided its design and b) describe its contribution to science (confirmation or refutation of a hypothesis, raising new questions, etc.).

The topics of the next class were the methodological characteristics of historical science. Based on the work of Cleland (2002), the concrete examples revealed that effects are underdetermined by their causes because a single cause or causal property is not sufficient to bring about the effect, whereas causes are overdetermined by their effects because a single effect can be sufficient to explain what happened, i.e., identify the causes. The case discussed was the end-Cretaceous (K-Pg) mass extinction.

The suggestion for the microteaching session was for teachers to show how they would teach about how historical researchers develop explanations, by relying on the history of science to show how particular explanations in historical natural science were developed and what their contribution was. Suggested readings were Cleland (2002, 2011) and Forber and Griffith (2011). The home assignment was for teachers to select a scientific discipline with a historical dimension (evolutionary biology, astronomy, geology) they are well familiar with and describe how scientists (a) obtain data and relate it to existing knowledge and (b) ask questions, test hypotheses, and develop explanations.

35.3.8 Class 9: Conceptual Change in Science

The ninth class focused on the idea of conceptual change in science. I started by explaining that conceptual change is produced by mental processes that create and alter mental representations after these are found to be incompatible with the available evidence. We analyzed the distinction between concepts and conceptions, the latter being the different meanings of or associated with particular concepts. I explained that conceptual change in science may involve the alteration/restructuring of existing concepts (the concept of contrivance/adaptation from Paley to Darwin), the change in the relations among existing concepts (the transition from a geocentric to a heliocentric system), or even the creation/invention of new concepts (the concept of gene).

After clarifying the nature of scientific concepts and conceptual change, we engaged in a detailed discussion of the development of Charles Darwin's theory of evolution by natural selection. This is a particularly good example of conceptual change that shows that this is a lengthy process rather than a sudden shift in one's views. The main idea was that Darwin worked on his theory for 20 years, while reading, collecting evidence, conducting experiments, and developing explanations. These processes resulted to a conceptual shift from his initial view of perfect adaptation to the idea of relative adaptation we find in *The Origin of Species* (Darwin 1859). The details of this process and the account of conceptual change presented in this class draw on Chapters 3 and 4 of Kampourakis (2014).

For the microteaching session, I noted that teachers could show how they would teach about conceptual change in science, by relying on the history of science to show how particular scientists developed new concepts or restructured old ones and what their contribution to science was. Suggested readings were Worrall (2008), Thagard (2003), Nersessian (1992), and Goldstein (2002). For the assignment, teachers were asked to select a historical case study of conceptual change they are well familiar with and describe the evidence and the thought processes that brought about conceptual change and the role of human creativity and insight in these processes.

35.3.9 Classes 10 and 11: Science and Ethics/Science and Religion; Philosophy of Science and History of Science

The aim of the next class was to show that science is a human activity, practiced in the context of a wider socio-cultural milieu. Because of this, science is influenced by this milieu but can also have an influence on it. This interaction is very clearly shown in the practice of science and the ethics of this practice, as well as in its interaction with religion. After clarifying the difference between ethics and morals, some ethical norms that should guide scientific reasoning and conduct were discussed such as honesty, objectivity, openness, freedom, fair credit allocation, respect for colleagues, intellectual property and laws, stewardship of research resources, social responsibility, humane treatment of animal subjects, and respect for human subjects. Then discussion focused on religion and its complicated interaction with science to show, through concrete examples, that there can be no war between science and religion because there are many different religious views among scientists and there are also many different attitudes toward science among religious people and theologians (see Chapter 2 of Kampourakis 2014).

The suggestion for the microteaching session was for teachers to select a case study from the history of science that is known to have raised ethical or religious issues and to describe the impact of the respective scientific knowledge on these issues. For homework, the teachers were also asked to select a case study from the history of science that was known to have raised ethical or religious issues and describe the impact of the respective scientific knowledge on these issues. Suggested readings were drawn from Resnik (2008) and Livingstone (2011).

The last class was a recapitulation of the topics discussed in each course while new cases from the history of science were introduced to show how one might teach about the various NOSK aspects. These cases spanned all NOSK aspects and all major disciplines (biology, chemistry, physics, geology). Bowler and Morus (2005) was suggested as an appropriate book to use for this purpose. The rationale and the approach for using these stories are described in more detail in Kampourakis and McComas (2010), with stories provided in McComas and Kampourakis (2015, also found as Chap. 30 in this volume).

Table 35.3 The topics participants selected to present in the microteaching sessions and the respective grade levels for which they designed these lessons

Topics	Grade
Strengths and Limitations of Scientific Models Found in the Middle School Classroom	Grade 8
Virtues of a Good Theory	Grade 11
Introduction to the Cell Theory: Characteristics of Scientific Knowledge	Middle/elementary science class
Free Fall and Conceptual Change in Science	Grade 10
The Law of Conservation of Mass	Grades 9–11
Teaching About Scientific Theories Through Plate Tectonics	Grade 9

35.3.10 The Microteaching Sessions

Finally, during the microteaching sessions, each participant gave a short (8 min) presentation of how he/she would use a particular science topic while making use of the concepts and methods from philosophy of science described during the course. Data from the microteaching sessions provided additional insight into the potential impact of the course components and organization. Participants had sent me their lesson plans before the first session. During the first session, they presented their lesson and received feedback both from me and from the other participants. Based on these comments, they revised both and delivered the new versions in the second session. The instructor and the other participants completed an evaluation form for the presentation, whereas the instructor also completed an evaluation form for the lesson plan. The evaluation forms where then collected by the participant, and based on these, he/she revised the lesson plan and presentation for the next microteaching session. Table 35.3 presents the topics that participants selected for their microteaching sessions and the respective grade. As is evident in this table, all participants prepared instructional material with an explicit connection to topics from philosophy of science discussed in the course.

35.4 Some Conclusions from the Implementation of the Course

Participants completed two questionnaires before and after the course. The results indicated that the explicit connection of philosophy of science content to NOSI/NOSK aspects for teaching can have an impact on participants' understanding of these aspects. Overall, most participants showed enhancement of their NOSK conceptions. Most participants held more informed views about the target NOSK aspects at the end of the experience. Most also generally showed a significant improvement of their understandings of NOSI, as by the end of the course, they exhibited a shift in their initial views of how science is done. Overall it seems that that this philosophy of science course had a positive impact on their NOS understandings (Kampourakis et al. 2013).

Except for the questionnaire, I asked participants to provide a written evaluation at the end of the course by answering the following four questions:

1. What topics of the course were ***most*** relevant to your personal and professional interests? What topics were the ***least*** relevant to your personal and professional interests?
2. What did you perceive to be the strengths of the course?
3. What did you perceive to be the weaknesses of the course?
4. How could the course be improved?

Also interesting were some of the participants' comments about the nature of the course at the end of it, when they were asked to complete an evaluation form for the whole course. One participant noted that:

> Still, I appreciate that for the most part I feel like I have completed a course that was a genuine introduction to the philosophy of science and not simply a teacher workshop on NOSK and SI, and I wouldn't want constant reference to the classroom to interfere with that. The microteaching sessions were very powerful though, as well…

Another participant said:

> All the topics taught were relevant to science education. In this course, I learned about the relevance of philosophic approach to scientific thinking. The study of knowledge and justified belief (Epistemology) helped to understand the necessary and sufficient conditions of knowledge for learning. The historical and experimental epistemic characteristics in science learning gave a new perspective of my understanding on scientific knowledge. The final two classes (Microteaching) where teachers shared their lessons showcased the best practices of science teaching. The scientific inquiry and nature of science was a part of every class during the entire course.

What is most interesting from the perspective of this chapter is the following comment by another participant, who answered the question: "What topics of the course were *most* relevant to your personal and professional interests? What topics were the *least* relevant to your personal and professional interests?

> Most relevant – 1. Discussion of NOS lists controversy at the beginning of the course – I should be more explicit in my own teaching about which key ideas about NOS or SI I am addressing. I also think the critique of this "list" idea is valuable (although I don't ultimately support it), in that it encourages us to look at a more expansive and nuanced view of the nature of science which may be helpful for addressing any particular case. This also, in a great way, framed an issue that I would consider throughout the course – how do we balance philosophy of science with the needs of students?

35.5 Conclusions and Implications

Professional development is very important in facilitating the desired changes in teachers' and consequently students' conceptions (i.e., how to help teachers obtain an adequate understanding of NOSI/NOSK aspects) (Lederman et al. 2012). This course contributes to this goal, and it managed to make an explicit connection between topics from the philosophy of science and NOS aspects. The science teachers who participated found this useful for better understanding NOS and for developing their own instructional materials.

Any conclusions regarding the impact of this course are limited because of the varying levels of experience of the participants and due to the difficulty of measuring the acquisition of NOS knowledge. However, these anecdotes do provide us with a useful foundation for further investigation of how a philosophy of science course for science teachers could be developed and what its contents should be to improve participants' NOS understandings. Most importantly, it can motivate teachers to delve into the relevant literature and develop their own understanding. Philosophy of science can enrich and inform science teaching. But for teachers to become knowledgeable about philosophy of science and develop philosophically informed educational materials, an entry point to the respective scholarship is required. We are concerned not only about what teachers *ought to* do but also about what they *can actually* do. This means that if we want them to teach about NOS, we need to provide them with the necessary conceptual tools in order for them to be able to do so. Teachers need to understand why philosophy of science matters for their work, but they also need a guide to understand it and meaningfully use it in their teaching.

References[1]

Abd-El-Khalick, F. (2005). Developing deeper understandings of nature of science: The impact of a philosophy of science course on preservice science teachers' views and instructional planning. *International Journal of Science Education, 27*(1), 15–42.

Achinstein, P. (2008). Evidence. In S. Psillos & M. Curd (Eds.), *The Routledge companion to philosophy of science* (pp. 338–348). New York: Routledge.

Arabatzis, T. (2008). Experiment. In S. Psillos & M. Curd (Eds.), *The Routledge companion to philosophy of science* (pp. 159–170). New York: Routledge.

Audi, R. (2011). *Epistemology: A contemporary introduction to the theory of knowledge* (3rd ed., pp. 298–308). New York: Routledge.

Barker, G., & Kitcher, P. (2013). *Philosophy of science: A new introduction*. Oxford: Oxford University Press.

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[1] Note, citations indicated with an asterisk are those provided to the participants to guide discussions in class.

Bartos, S. A., & Lederman, N. G. (2014). Teachers' knowledge structures for nature of science and scientific inquiry: Conceptions and classroom practice. *Journal of Research in Science Teaching, 51*(9), 1150–1184.

Bowler, P. J., & Morus, I. R. (2005). *Making modern science: A historical survey*. Chicago/New York: The University of Chicago Press.

∗ Brigandt, I. (2013). Explanation in biology: Reduction, pluralism, and explanatory aims. *Science & Education, 22*(1), 69–91.

Capps, D. K., & Crawford, B. A. (2013). Inquiry-based instruction and teaching about nature of science: Are they happening? *Journal of Science Teacher Education, 24*(3), 497–526.

Cleland, C. E. (2002). Methodological and epistemic differences between historical science and experimental science. *Philosophy of Science, 69*, 474–496.

Cleland, C. E. (2011). Prediction and explanation in historical natural science. *British Journal of Philosophy of Science, 62*, 551–582.

Curd, M., & Psillos, S. (Eds.). (2013). *The Routledge companion to philosophy of science* (2nd ed.). New York: Routledge.

El-Hani, C. N. (2014). Kampourakis, K. (Ed.) (2013). The philosophy of biology: A companion for educators. *Science & Education, 23*(6), 1381–1402.

Forber, P., & Griffith, E. (2011). Historical reconstruction: Gaining epistemic access to the deep past. *Philosophy and Theory in Biology, 3*, e203.

Franklin, A. (2012). Experiment in physics. In: Edward N. Zalta (Ed.), *The Stanford encyclopedia of philosophy* (Summer 2012 Edition). http://plato.stanford.edu/archives/sum2012/entries/physics-experiment

French, S., & Saatsi, J. (2011). *Continuum companion to philosophy of science*. London: Continuum.

Giere, R. N. (2006). *Scientific perspectivism*. Chicago: The University of Chicago Press.

Godfrey Smith, P. (2003). *Theory and reality: An introduction to philosophy of science*. Chicago: The University of Chicago Press.

∗ Goldstein, B. R. (2002). Copernicus and the origin of his heliocentric system. *Journal for the History of Astronomy, 33*, 219–235.

Hacking, I. (1983). *Representing and intervening: Introductory topics in the philosophy of natural science*. Cambridge: Cambridge University Press.

Herman, B. C., Clough, M. P., & Olson, J. K. (2013). Teachers' nature of science implementation practices 2–5 years after having completed an intensive science education program. *Science Education, 97*, 271–309.

∗ Hitchcock, C. (2008). Causation. In S. Psillos & M. Curd (Eds.), *The Routledge companion to philosophy of science* (pp. 317–326). New York: Routledge.

Kampourakis, K. (2013a). *The philosophy of biology: A companion for educators*. Dordrecht: Springer.

Kampourakis, K. (2013b). Teaching about adaptation: Why evolutionary history matters. *Science & Education, 22*(2), 173–188.

Kampourakis, K. (2014). *Understanding evolution*. Cambridge: Cambridge University Press.

Kampourakis, K. (2016). The "general aspects" conceptualization as a pragmatic and effective means to introducing students to nature of science. *Journal of Research in Science Teaching, 53*(5), 667-682.

Kampourakis, K., & McComas, W. F. (2010). Charles Darwin and evolution: Illustrating human aspects of science. *Science & Education, 19*(6–8), 637–654.

Kampourakis, K., Lederman, N. G., Lederman, J. S., & Jimenez, J. P. (2013, April). *The influence of a philosophy of science course on teachers' views of scientific inquiry and nature of scientific knowledge*. Paper presented at the 2013 NARST Annual International Conference, Rio Grande, Puerto Rico.

Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth graders' views of nature of science. *Journal of Research in Science Teaching, 39*, 551–578.

∗ Lederman, N. G. (2007). Nature of science: Past, present, and future. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 831–879). Mahwah: Erlbaum.

Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., & Schwartz, R. S. (2002). Views of nature of science questionnaire (VNOS): Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching, 39*(6), 497–521.

Lederman, J. S., Lederman, N. G., Kim, B. S., & Ko, E. K. (2012). Teaching and learning of nature of science and scientific inquiry: Building capacity through systematic research-based professional development. In M. S. Khine (Ed.), *Advances in nature of science research: Concepts and methodologies* (pp. 125–152). Dordrecht: Springer.

∗ Lipton, P. (2008). Inference to the best explanation. In S. Psillos & M. Curd (Eds.), *The Routledge companion to philosophy of science* (pp. 193–202). New York: Routledge.

∗ Livingstone, D. N. (2011). Which science? Whose religion? In J. H. Brooke & R. Numbers (Eds.), *Science and religion around the world* (pp. 278–296). New York: Oxford University Press.

∗ McComas, W. F. (1998). The principal elements of the nature of science: Dispelling the myths. In W. F. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 41–52). Dordrecht: Kluwer.

McComas, W. F., & Kampourakis, K. (2015). Using the history of biology, chemistry, geology, and physics to illustrate general aspects of nature of science. *Review of Science, Mathematics and ICT Education, 9*(1), 47–76.

∗ McMullin, E. (2008). The virtues of a good theory. In S. Psillos & M. Curd (Eds.), *The Routledge companion to philosophy of science* (pp. 498–508). New York: Routledge.

∗ Nersessian, N. J. (1992). How do scientists think? Capturing the dynamics of conceptual change in science. In R. N. Giere (Ed.), *Cognitive models of science* (pp. 3–45). Minneapolis: University of Minnesota Press.

Niaz, M. (2009). *Critical appraisal of physical science as a human enterprise: Dynamics of scientific progress*. Dordrecht: Springer.

Osborne, J., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. (2003). What "ideas-about-science" should be taught in school science? A Delphi study of the expert community. *Journal of Research in Science Teaching, 40*(7), 692–720.

Psillos, S. (2007). *Philosophy of science A-Z.* Edinburgh: University of Edinburgh Press.

∗ Resnik, D. B. (2008). Ethics of science. In S. Psillos & M. Curd (Eds.), *The Routledge companion to philosophy of science* (pp. 149–158). New York: Routledge.

Rosenberg, A. (2005). *The philosophy of science: A contemporary approach* (2nd ed.). London: Routledge.

∗ Thagard, P. (2003). Conceptual change. In L. Nadel (Ed.), *Encyclopedia of cognitive science* (Vol. 1, pp. 666–670). London: Macmillan.

∗ Woodward, J. (2008). Explanation. In S. Psillos & M. Curd (Eds.), *The Routledge companion to philosophy of science* (pp. 171–181). New York: Routledge.

∗ Worrall, J. (2008). Theory change in science. In S. Psillos & M. Curd (Eds.), *The Routledge companion to philosophy of science* (pp. 281–291). New York: Routledge.

Chapter 36
Learning Aspects of Nature of Science Through Authentic Research Experiences

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36.1 Introduction

The authenticity of a scientific investigation can be described in terms of the degree to which the practices involved share epistemologic and cognitive characteristics with those practiced by professional scientists (Chinn and Malhotra 2002). The question is how participation in authentic science activities/investigations leads – if it does – to the development of sophisticated nature of science (NOS) understandings among science learners. We postulate that science learning experiences with greater authenticity will result in improved NOS understandings. Research clearly suggests the merits of NOS teaching and learning that is both explicit and reflective (Lederman 2007). In other words, NOS instruction ought to be intentionally designed to have a positive impact on learners in order to maximize that effect. Thus, it is crucial that science educators consider how to pair participation by

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_36

science learners in authentic scientific investigation with explicit approaches to NOS teaching and learning. Issues such as these provide the framework for this chapter.

The *Framework* that guided the development of the *Next Generation Science Standards* (NGSS) in the USA emphasizes that by engaging in the practices of science, students will learn about the nature of the resulting science knowledge and how scientists go about developing that knowledge through their professional endeavors (National Research Council [NRC] 2012). However, an abundance of research (e.g., Bell et al. 2003; Khishfe and Abd-El-Khalick 2002) has shown that by merely engaging in the practices of science (even highly authentic work conducted in professional settings), students will not necessarily develop a consistently informed perspective of many targeted aspects of NOS.

That said, recent research has demonstrated that while an explicit/reflective approach to NOS instruction contextualized within an authentic research apprenticeship for high school science learners was most effective, some learners in the apprenticeship learned about certain aspects of NOS (i.e., subjectivity, creativity) even in the absence of explicit NOS instruction (Burgin and Sadler 2016). Since this finding seems to stand in direct opposition to previous work, we need to understand why this is the case. Perhaps the authentic nature of the scientific work in this research apprenticeship, which could not have taken place in a traditional science classroom with thirty plus students and less than ideal scientific equipment, was a factor in learners' developing greater understanding of certain NOS aspects.

Given the conflicting results of previous studies, there is a need within the science education community to establish a clear research agenda to systematically examine the relationship between engaging in the practices of science and the development of NOS understandings discussed in current reform documents (NRC 2012). We argue that the relationship between engaging in scientific practices and the development of NOS understandings is complex, nuanced, and contextual. We acknowledge that the further removed one is from genuine scientific research, the less authentic is the work being engaged in from a canonical perspective (Buxton 2006). For the purposes of this chapter, we draw from this canonical perspective when defining authenticity. The most authentic experiences are those that model the entirety of the scientific practices engaged in by professionals (i.e., from the development of a question to the reporting of results) in addition to embedding the learner in an authentic scientific context (e.g., laboratory, field, etc.) and the authenticity of the findings (i.e., genuine contributions to scientific knowledge). Because the ultimate authentic experience in scientific investigation would involve authentic context, it is critical that practicing scientists engage with learners of science at all levels to share their research and how they conduct their work.

In this chapter, we are pleased to present findings from our own work that suggest that what NOS aspects are and how they are involved in the generation of scientific knowledge can both be learned in various contexts that fall on a continuum of authenticity. Figure 36.1 displays these contexts in order of increasing authenticity.

We begin our discussion by describing authenticity within traditional K-12 school science contexts and end with experiences in professional science contexts.

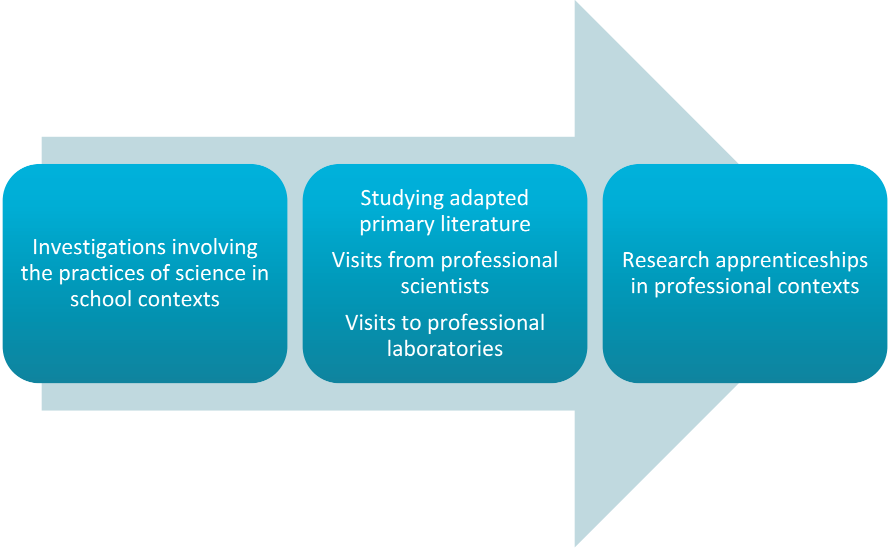


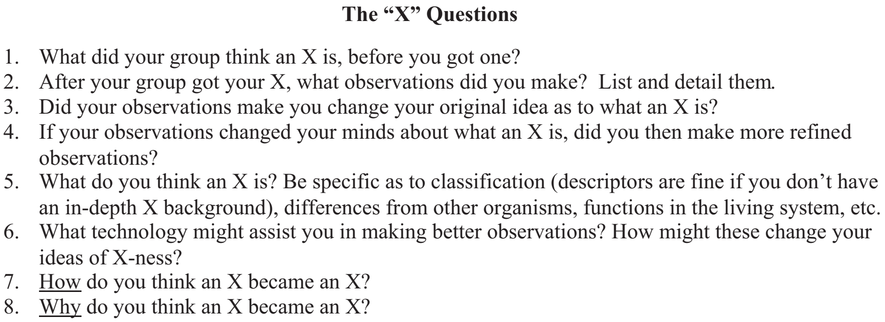
Fig. 36.1 Authentic activities for the learning of NOS in order of increasing authenticity of context

Specifically, we discuss how our individual research projects have led to results with specific implications for the teaching and learning of NOS through the examination of and/or participation in the actual or simulated authentic work of professional scientists. We conclude with a discussion of various models for teacher preparation and professional development, preparation of scientific literature for classroom use, and the training of host/mentor scientists that provide the possibility of overcoming and resolving some of the challenges to learning about NOS in these contexts.

36.2 Aspects of Authentic Investigations in K-12 Learning Settings

Experiences in the K-12 classroom are limited by time, space, expertise, and availability of equipment. However, students can have experiences that provide insight into the world of a scientist and how new scientific knowledge is generated by scientists. Two investigations, *What is X?* (Matkins 2009) and *Seeing Like an Astronomer*, developed by the American Museum of Natural History (2003), were used to support development of students' NOS ideas in a statewide initiative. One of the goals of this initiative was to engage learners in learning about NOS. Both investigations focus on developing students' observing and inferencing skills and linking these through explicit discussion to key NOS ideas.

What Is X? This strategy was developed to help students gather evidence about an unknown organism and to consider how a scientist would approach their study of



The “X” Questions

1. What did your group think an X is, before you got one?
2. After your group got your X, what observations did you make? List and detail them.
3. Did your observations make you change your original idea as to what an X is?
4. If your observations changed your minds about what an X is, did you then make more refined observations?
5. What do you think an X is? Be specific as to classification (descriptors are fine if you don’t have an in-depth X background), differences from other organisms, functions in the living system, etc.
6. What technology might assist you in making better observations? How might these change your ideas of X-ness?
7. How do you think an X became an X?
8. Why do you think an X became an X?

Fig. 36.2 The NOS investigation: What is X?

the unknown organism, using such unfamiliar objects as tadpoles, pill bugs, geodes, or fossil crinoids (Matkins 2009). The lesson begins with the teacher showing one or two examples of the specimen and asking students to make observations about it. At this point, students do not have a close-up view of the specimen. The teacher circulates around the room and shows the object while continuing to ask students for their observations. A document camera might be used to share the object with the entire class in more detail. The teacher then asks “how might we learn more about this object?” and at this point accepts all responses.

Students, working in small groups, are then given a sample of the specimen and the “What is X?” Worksheet (Fig. 36.2). The worksheet has two foci: the first is questions that engage the students in recording data (i.e., their observations) to continue learning about the specimen. The second is questions that ask the students to consider how scientists approach their work. (These questions address NOS aspects.) The questions prompt students to consider how specific tools might help them learn more (Science and Technology), how their thinking about the specimen changes as they make more observations, how technology might help them, how certain they feel about their ideas of what the specimen is (subjectivity is a factor), how the specimen became the specimen, and the philosophical question of why the specimen is what it is (science has limits). If they ask, students are provided a hand lens and other tools (e.g., a weak acid solution or water) to examine the specimen. When the students have completed their study of the specimen, the teacher leads a reflective discussion about NOS by asking questions such as “What skills that scientists use did you use today?,” “How did you act like a scientist in the investigation we did today?,” and “How did the investigation and the questions help you think about how scientists approach their work?.” These questions help link the lesson to the different aspects of NOS (e.g., observation and inference) addressed in the lesson.

What Is X?

Many students have not been exposed to open-ended questions in science, questions not easily answered by looking in a textbook. Such questions, when accompanied by skillful questioning and explicit references to aspects of NOS, can reveal how science is done, how scientific knowledge is created and communicated, and how science is influenced by cultural and personal experiences. Students often think of scientific terminology such as "life cycle" and "amphibian" as ways to describe or define something. This simple exercise is designed to engage students in an investigation that is a model for how science is done and what science cannot do.

Seeing Like a Scientist Another activity that helps students build observing and inferencing skills and explicitly link their thinking to the idea that scientists use empirical evidence to develop knowledge is *Seeing Like a Scientist*. Initially, we used *Seeing Like an Astronomer* (American Museum of Natural History 2003), to focus on NOS during an astronomy unit. In *Seeing Like an Astronomer*, students are given an opportunity to develop an understanding of the role of observation in astronomy and how different tools have aided our understanding of the universe. The approach used in the Astronomer activity is easily modified to showcase other scientific fields as well (see below) so we renamed it *Seeing Like a Scientist*.

In the first phase, the teacher sets up a display of random objects (e.g., of a variety of sizes) at the front of the room before class and covers it up. After turning off the lights and having students move to the back of the classroom, they are asked to make observations of the object(s) at the front of the room for 2 min without talking. The teacher then covers up the display, turns on the lights, and asks students to share their observations with the entire group. The teacher listens for observations and helps students rephrase inferences into observations as necessary.

In a second round, students are given different tools (e.g., flashlights, binoculars, or decreased distance from the object(s)) that provide additional insight into the object(s) in the dark. After turning off the lights, the students make observations for another 2 min using their new tools. Students then share their new observations of the object(s). The teacher leads a discussion that guides students to consider the advantages provided by the tools and how new technologies have helped us to understand our universe. (Here the NOS focus is that science is distinct from technology and engineering.) The students then examine how scientists have come to better understand our universe through time by learning from the teacher via photographs (included in the chapter) about the technology used from the time of Galileo up to current satellites and space probes (science is tentative, durable, and self-corrected).

Seeing Like an Astronomer fits well when teaching about space and space explorations, and the activity could easily be modified to reflect discoveries in different fields of science. For example, in a unit on oceans and ocean resources, teachers implemented *Seeing Like a Physical Oceanographer*. In this activity, teachers selected tools for mapping the seafloor. They substituted a sounding box for observing the object in the dark. Teachers showed students pictures and discussed how maps of the seafloor have been developed through history. Then, students "mapped the seafloor" using a sounding box and graphed the resulting data to create a graph of the ocean floor.

For a unit on human impact on the environment, the students took on the role of a field ecologist. Students explored the living organisms inside a specified area of study bounded by something such as a rope tied in a circle, a hula hoop thrown randomly on the grass, or a 3D cube made of PVC pipe (Wilson 2010). The investigation of living organisms within a specified area of study is fairly common (Wilson 2010). As the students explored, they were provided other tools, such as hand lens, trowels, specimen boxes, nets, or field guides, to aid in their exploration. Similar to the *Seeing Like an Astronomer* activity, students discussed what they were able to observe before and after using the tools. During the discussion, students linked what they had done in the activity to how field ecologists investigate the natural world and how they have incorporated new technologies, such as Global Positioning Systems, into their work (Scientific Method; Science and Technology).

Each of these activities provides a model to deepen students' understanding of how scientists work in that field and a strong historical link to how scientific ideas have changed over time. Both investigations, *What is X?* and *Seeing Like a Scientist*, provide students with the opportunity to use practices of science, like observing and inferring, and to explicitly discuss how their investigations link to various aspects of NOS. These activities provide experiences that are on the lower end of authenticity because while they model a subset of the scientific practices engaged in by professionals, they do not embed the learner in an authentic scientific context, and the findings of these activities are not necessarily authentic.

36.3 Adapting Primary Literature

The APL approach to teaching about NOS was developed at the Weizmann Institute of Science and is included in the Israeli biology curriculum as one of the elective topics available to high school teachers (Israeli Ministry of Education 2010; Yarden et al. 2001). APL refers to an educational genre specifically designed to enable the use of research articles in teaching biology in high school.

To provide teachers with an adequate instructional strategy for the enhancement of inquiry learning, Yarden et al. (2001) developed the conversational model and suggested it as suitable for APL-based teaching. The model is based on an iterative process involving a constructivist discourse between the students and the article, which includes three steps: (1) the students read one section of the article together in the classroom, (2) they raise questions about the section, and the teacher writes the questions on the board, and (3) the students predict the outcomes of suggested experiments, in order to answer at least some of the questions. By repeating those steps in subsequent sections of the article, the students can obtain answers to their questions and can verify their predictions in the class discussion that follows.

APL supports explicit NOS instruction in high school biology classes (Tsybulsky 2013, 2018). First, scientific papers written by professional scientists are adapted for the reading level of high school students, while maintaining the structure of the research article and some of the original results. The work of Yarden et al. (2001) guides the modifications (e.g., giving the novice reader basic background information that was either omitted from or simply quoted in the original paper and a description of the main principles of the methods section). The results from the primary research and main figures are maintained, potentially with slight modifications, but details of amounts, solution compositions, results from secondary questions, etc. are omitted to simplify and streamline the focus of the paper. Finally, the discussion is expanded so that students can understand it more easily.

The students read two such papers: one in cell biology and one in ecology. Both during and after the reading, the students answer questions focused primarily on the following NOS aspects: science is tentative, durable, and self-corrected, creativity is vital, and there are social/cultural influences. Although the study was in biology, we believe that APL approach can be implemented in other sciences. Through dialogue with each other about scientific texts, the students are exposed to the work of scientists in an authentic context.

36.4 Authentic Research Lab (ARL)

This approach to NOS teaching was developed at the Hebrew University of Jerusalem (Tsybulsky et al. 2012, 2017a, b) and was designed to enhance NOS understanding among high school students. Hodson and Wong (2014) claim that students can attain a richer NOS understanding through direct contact with practicing scientists; thus, the ARL approach engages students in a 4-h visit to a university with guided learning experiences prior to and during the visit. Lab visits included a presentation of the research and a broader perspective of scientific research. The visits also included small lab tasks (manipulating scientific equipment) to demonstrate the methodology of the research, but the emphasis was on discourse between students and graduate students about various aspects of NOS.

Implementation of the ARL method follows the model of Orion (1993) for development and implementation of educational field trips (preparation, field trip, summary):

1. In-class preparation: (a) Students view a multimedia presentation about the labs to be visited and their personnel, including the researchers, the research questions addressed, the methods, and equipment; (b) Students read and discuss brief writings about the research carried out in these labs with their teacher. These reading materials, prepared by our team, are formatted according to Schwab's "narratives of inquiry" (Schwab 1962) and include the labs' research topics, a description of a problem, and subsequent research plan developed to investigate the problem and data and the research team's interpretation of the data; (c) Students prepare questions to ask the graduate students leading the lab visits. The questions focus on different NOS aspects, scientific inquiry, and subject area. The students received clear instruction from their teachers in how to prepare written questions for the graduate students. They were guided to ask questions that interest them regarding the content matter, as well as to raise questions and challenges regarding the research methodology and the research process itself.

2. Lab visits: Each student group visits two biology labs (cell biology and ecology are favorites) – each for 90 min, on the same day. A graduate student in each lab guides the students, describing his/her own research in the context of the NOS aspects of our study to provide an *authentic narrative of inquiry*. The graduate student also responded to the students' prepared questions and led a broader discussion. The students participated in small hands-on inquiries designed to allow the students to interact with scientific equipment and engage in a dialogue about the research of the lab and how it reflects NOS. In the discussions, various aspects of NOS come up from all three NOS domains (tools and products of science, special nature of scientific knowledge, human elements in science).
3. In-class summary: The aim of the summary was to help students assimilate the contents of the visit both emotionally and cognitively and to allow reflective and meta-cognitive thinking. The students, led by their teacher, wrote reflective comparisons of the two labs visited. They also extended their NOS learning by reading and discussing a "historical narrative" we designed about DNA's discovery, including questions explicitly focused on NOS aspects (e.g., Do you think the scientific community should change its mind on the basis of a single, even extremely successful experiment?).

Direct contact with scientists in their research labs provides a non-linear, authentic, exciting environment to enhance NOS understanding. ARL provides a greater level of authenticity than the three activities described previously that take place in a school setting.

36.5 Research Apprenticeships in Professional Contexts

It can be argued that the most authentic context for practicing science is one in which that scientist is at work with others conducting scientific research/investigations in some appropriate setting (e.g., laboratory investigations/field work). Research apprenticeships have been used frequently for a variety of learners including secondary and undergraduate students and for preservice and in-service teachers in order to provide just such an authentic context for the practice of science (Sadler et al. 2010).

Among the potential positive outcomes of participation in research apprenticeships reported is the development of sophisticated NOS understanding (e.g., Burgin and Sadler 2016; Charney et al. 2007; Schwartz et al. 2004). In each of these studies, gains in NOS understandings were linked to a feature of the experience that explicitly addresses NOS. This may be through carefully designed reflective experiences such as written journal entries, direct conversations with scientists and their graduate students about the generation of a research question and methodologies, for example, and/or careful placement of the participant in a highly collaborative and creative laboratory environment. In particular, students in one study benefitted from being placed in laboratories where the work being done involved more than just routine tasks like sample preparation and the recording of data (Burgin and Sadler 2016). Specifically, learners who are embedded in a collaborative laboratory group may intentionally encounter the subjective and tentative nature of scientific knowledge as diverse ideas are tested and considered and data are analyzed as colleagues work together. However, one caution is that it is unlikely that NOS understandings will be impacted in a research apprenticeship setting unless a component of the apprenticeship is designed to intentionally address NOS understandings. This may be particularly true for those NOS goals (i.e., the distinctions between theories and laws) that are not often encountered when engaging in authentic scientific research (Bell et al. 2003; Burgin and Sadler 2016).

When learners are placed in highly authentic contexts such as research apprenticeships, they have the opportunity to collect and analyze data that contributes to the generation of new scientific knowledge. This might be the most "authentic" of the various ways for a learner of science to be explicitly instructed about NOS. Of course, it would be difficult for such an experience to take place in a traditional science classroom.

Perhaps the closest approximation to this fully authentic experience comes through participation in a science fair project, but few of these result in the production of genuinely novel findings. That being said, there are characteristics of science fair projects that carry with them other aspects of authenticity. First, they allow the learner to develop a personally relevant and "do-able" research question and to design the methods to analyze that question. Involvement in these aspects of research has the potential to help students make explicit connections to NOS aspects such as the role of evidence and the importance of creativity. Second, designing and carrying out a science fair project also may dispel the myth of the stepwise scientific method, as students do not necessarily follow such a deductive path in conducting their investigation, and not all investigations conducted in science fair projects are experimental in nature, as "the" scientific method would suggest. Third, furthermore, students conducting science fair projects could be required by science teachers to reflect on the role that creativity played in the development of their project as they prepare for its presentation. However, it should be pointed out that many science fair guidelines/rubrics require students to have a hypothesis, an expectation that may actually reinforce the idea that all scientific investigations follow the same methodology (McComas 2011).

Another strength of a science fair in comparison to a research apprenticeship is the potential for large numbers of students to participate. Research apprenticeships are less available to students and tend to attract a certain caliber of student likely already interested in science as a career option.

In contrast to the traditional science fair, in the typical research apprenticeship, the learner is brought into a preexisting research project with a previously defined research question and a well-developed procedural protocol (Burgin and Sadler 2016). There are good reasons for this, namely that authentic scientific research takes time to complete and that entire research groups spend their careers working to extend and further knowledge in regard to one very specific research agenda. This actually could represent an opportunity for explicit NOS instruction by the mentor and/or the facilitators of the research apprenticeship. Mentors ought to be encouraged to have conversations with their apprentices about the development of the project before the apprenticeship and where the project will go after the apprenticeship ends. Such expectations could be provided to the mentor scientists and graduate students in a sort of handbook when they agree to serve as mentors in a research apprenticeship program.

36.6 Resolving Challenges to NOS Instruction in Authentic Environments

Each of the approaches and contexts described above has unique challenges for the classroom teacher and/or scientist mentors (Table 36.1). The sections that follow describe how such challenges may be resolved.

Professional Development for Teachers Research indicates that many K-12 teachers do not understand key NOS ideas or know how to effectively integrate authentic experiences to develop students' accurate NOS conceptions. This becomes a challenge when those teachers plan to include authenticity in instruction. Therefore, to develop teachers' capacity to engage students in authentic investigations in the K-12 classroom, a three-pronged Learn-Try-Implement approach to professional development (PD) might be applied (Maeng et al. 2016). In this approach, teachers first *learn* about NOS through several modeled explicit NOS activities, then they practice (*try*) teaching explicit NOS in several lessons during a summer science camp or in their classroom, and finally they engage in planning an entire science unit for implementation during the school year that explicitly embeds and addresses the different aspects of NOS during lessons (*implement*).

During the *learn* portion of the approach, teachers are pre-assessed on their NOS conceptions through a card sort that includes accurate and inaccurate statements about NOS. Teachers work individually to sort the cards into agree, disagree, and not sure piles. Then, they share one of their not sure cards with a small group and one or two with the whole group. Revisiting their card sort during the additional learning activities provides a reflective opportunity to consider how their understanding has changed.

To model explicit, reflective NOS instruction, teachers engage in the previously described activities, “What is X?” and “Seeing Like a Scientist.” Additional activities designed to move teachers from understanding to implementing NOS include reading case scenarios that model actual teacher practice and identifying whether the NOS instruction is explicit or not, and if not, proposing ways that explicit NOS instruction could be incorporated. This sequence of activities, embedded within the Learn-Try-Implement framework, provides teachers with both an understanding of NOS and strategies for how to teach NOS explicitly. This model developed teachers' understandings and skills to integrate explicit NOS into their classroom

Table 36.1 Approaches to authentic NOS experiences, their pros and cons, and necessary preparation

Authenticity (least to greatest)	Approach	Pros	Cons	Preparation needed
Classroom activities: What is X?, seeing like a scientist	Activities designed to develop observing and inferring skills and linking these through discussion to key ideas about NOS	Easily replicable by teachers Materials are easily accessible Can be done in the classroom Discussion with students to highlight explicitly aspects of NOS Students become comfortable with identifying how their lessons incorporated NOS	Students not engaged in all of the science practices Students not in real laboratory setting Students not generating new scientific knowledge	Professional development necessary for teachers to deepen understanding of aspects of NOS and how to make their discussion with student explicit
APL	Use of research articles	Students read modified articles that share research findings from actual scientists. Discussion with the teacher is key to highlighting the aspects of NOS	Students not engaged in the science practices (reading about them), students not in real laboratory setting, students not generating new scientific knowledge	Professional development for teachers on the approach and how to implement Research articles must be modified for reading level
ARL	Visit to two research labs for 90 min each and in class summary and extension via reading and discussion	Preparation presentation to orient students to each lab Visit in lab and manipulate lab equipment Interaction with actual scientist	Extensive preparation and coordination required Must work with scientist to develop pre-presentation. Length of visit is short Students not generating new scientific knowledge	Professional development for teachers on the approach and how to implement. Professional development for the mentors on how to work with teachers and students and how to be explicit about NOS. Assistance in developing the research narrative

(continued)

Table 36.1 (continued)

Authenticity (least to greatest)	Approach	Pros	Cons	Preparation needed
Research apprenticeship	Students working in an authentic research context	Students are actually in a scientific lab working alongside scientists	Extensive preparation and coordination required NOS must be explicitly built into the apprenticeship or it will not be addressed with the students	Professional development for the mentors on how to work with students and how to be explicit about NOS

instruction, and they were excited to have students talk about how scientists approach their work and see students' positive responses to their NOS instruction (Maeng et al. 2016).

For the *APL and ARL* approaches, a common challenge involves garnering the teachers' cooperation and preparing them for the different mode of instruction these approaches necessitate. To support teachers' understanding and capacity to teach through these instructional modes, the teachers engage in an intensive 2-day workshop that includes lectures on NOS, an explanation of the rationale of the APL and ARL approaches, and practical experience based on modeling (Tsybulsky 2013). We recommend that teachers who lack a strong scientific research background receive a longer and more intensive preparation to enable them to successfully adapt these approaches to their classroom instruction.

Preparation of Scientific Literature for APL The main challenge encountered for the APL approach involved adaptation of the current scientific literature for high school students. This is time consuming and requires the cooperation of the researchers whose work is being adapted. Therefore, we recommend the use of up-to-date studies written by researchers at universities close to the schools in which APL will be applied. Alternately, students can prepare questions for the researchers (after they read the article) and send these questions by e-mail to the researchers to create a "virtual dialogue" between the students and the researchers. Additional variations might involve a Skype meeting or visit of the researchers to the classroom.

Supporting Scientist Mentors For ARL and research apprenticeship approaches, both of which immerse students directly in scientists' laboratories, logistical and administrative challenges regarding scheduling and transportation issues exist. Preparation of the scientist team is critical to helping them communicate their work effectively to non-scientists and students and to address logistics of school-aged children visiting a laboratory space. A workshop for mentor scientists or selected research manuscripts from science education literature could be provided to these mentors to help them think about NOS and how they could explicitly incorporate it into their work with science learners.

In the ARL approach, an advanced Ph.D. candidate underwent a 3-day training session in preparation for having students visit the lab (Tsybulsky 2013). This training session included two main components: (1) the elements of "successful guidance" of students and (2) the construction of the "research narrative." Regarding how to guide students, instruction focused on using level-appropriate scientific terminology, creating a successful flow of activities for the students, providing clear and organized instructions throughout the visit, facilitating the discussion, and creating stations at which students can receive guidance and can experience the activities at the lab.

Regarding the construction of the "research narrative" in the ARL approach, the researchers received help in creating the necessary narrative to ensure that it addressed the following: (1) what was known in the field before the researchers commenced their study, (2) why this study interested them, (3) the research questions guiding the study and how they changed throughout the course of the study, (4) the methods utilized, and (5) the findings of the study. In addition, researchers addressed the collaborations within the lab and between other labs at the university and beyond.

For the full *research apprenticeships*, in which students spend a longer time in the laboratory setting and take a more active approach than in the ARL method, it is imperative that the program developer intentionally provide training opportunities for mentor scientists and graduate students who will be hosting science learners in their laboratories. These professional scientists need to be able to have conversations with the apprentices placed in their labs that explicitly target relevant NOS ideas (e.g., Bell et al. 2003; Burgin and Sadler 2016). Similar to the ARL method, it is vital that mentors introduce students to the processes that led to the development of research questions and methods before the apprentice ever sets foot into the lab. Additionally, apprentices should have conversations with mentors about what will happen with their research after the apprenticeship ends. Finally, mentors should be provided with opportunities to reflect on the NOS aspects an apprentice may most likely encounter in the course of their scientific research. For example, the nuanced differences between theories and laws in science are less likely to be experienced in a research apprenticeship than are aspects such as the creative NOS, subjective NOS, and empirical NOS (Burgin and Sadler 2016).

36.7 Conclusions

The approaches to authentic NOS instruction described above suggest NOS can be learned in various contexts that fall on a continuum of authenticity from traditional school science classrooms to professional science laboratory contexts (Table 36.2).

Each approach engaged K-12 science learners in scientific investigations that portray the work of professional scientists to improve students NOS understandings. Our research provides evidence that activities that provide students a window into the authentic practices of scientists upon which they can reflect support the

Table 36.2 Level of authenticity for each approach using the canonical perspective of authenticity

	Authenticity criteria		
	Models the entirety of the scientific practices engaged in by scientists (from the development of a question to the reporting of results)	**Authentic context** (laboratory, field, etc.)	**Authenticity of findings** (genuine contributions to scientific knowledge)
Classroom activities	Partial depending on the activity	No	No
APL	Partial	No	Partial (through reading)
ARL	Partial	Yes	Partial (listening to scientists)
Research apprenticeship	Yes or partial depending on how embedded the apprentice is in the lab setting and the duration of the experience	Yes	Yes (generate)

development of their accurate NOS conceptions. Future studies should explore whether the value of authentic experiences in NOS learning is greater than an activity that was even less authentic than those described in this chapter, such as reading an article about a scientist or reviewing the different aspects of NOS after an investigation. Developing robust experiences for learners in any context is not without challenges, and our work provides some examples of how to support teachers and scientists through professional development to intentionally and explicitly address NOS in their work with students.

References

American Museum of Natural History (2003). Seeing like an astronomer. *Partnership between NASA and the American Museum of Natural History: Furthering our joint educational mission. This material is based upon work supported by the National Aeronautics and Space Administration under Grant No. NAG5–11139.* Retrieved March 1, 2012, from http://www.haydenplanetarium.org/downloads/universe/.../Seeing_Like_Astronomer.pdf

Bell, R. L., Blair, L. M., Crawford, B. A., & Lederman, N. G. (2003). Just do it? Impact of a science apprenticeship program on high school students' understandings of the nature of science and scientific inquiry. *Journal of Research in Science Teaching, 40*(5), 487–509.

Burgin, S. R., & Sadler, T. D. (2016). Learning nature of science concepts through a research apprenticeship program: A comparative study of three approaches. *Journal of Research in Science Teaching, 53*(1), 31–59.

Buxton, C. A. (2006). Creating contextually authentic science in a "low-performing" urban elementary school. *Journal of Research in Science Teaching, 43*(7), 695–721.

Charney, J., Hmelo-Silver, C. E., Sofer, W., Neigeborn, L., Coletta, S., & Nemeroff, M. (2007). Cognitive apprenticeship in science through immersion in laboratory practices. *International Journal of Science Education, 29*(2), 195–213.

Chinn, C. A., & Malhotra, B. A. (2002). Epistemologically authentic inquiry in schools: A theoretical framework for evaluating inquiry tasks. *Science Education, 86*(2), 175–218.

Hodson, D., & Wong, S. L. (2014, August). From the Horse's Mouth: Why scientists' views are crucial to nature of science understanding. *International Journal of Science Education, 693*, 1–27.

Israeli Ministry of Education. (2010). *Syllabus of biological studies for high schools from all sectors of society*. Tel Aviv: The Ministry of Education, Culture and Sport.

Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth graders' views of nature of science. *Journal of Research in Science Teaching, 39*(7), 551–578.

Lederman, N. G. (2007). Nature of science: Past, present, and future. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 831–879). New York: Routledge.

Maeng, J.L., Bell, R.L., St. Clair, T., Whitworth, B.A., & Gonczi, A.L. (2016). *From professional development to practice: Elementary teachers' understandings and enactment of nature of science instruction.* A paper for the annual meeting of NARST, Baltimore.

Matkins, J. J. (2009). *What is X?* Personal Communication and Collaboration on VISTA I3 US DOE funded grant- http://vista.gmu.edu/ (2010–2015).

McComas, W. F. (2011). Science fairs: A new look at an old tradition. *The Science Teacher, 78*(8), 34–38.

National Research Council [NRC]. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: The National Academies Press.

Orion, N. (1993). A model for the development and implementation of field trips as an integral part of the science curriculum. *School Science and Mathematics, 93*(6), 325–331.

Sadler, T. D., Burgin, S., McKinney, L., & Ponjuan, L. (2010). Learning science through research apprenticeships: A critical review of the literature. *Journal of Research in Science Teaching, 47*(3), 235–256.

Schwab, J. J. (1962). *The teaching of science as inquiry*. Cambridge, MA: Harvard University Press.

Schwartz, R. S., Lederman, N. G., & Crawford, B. A. (2004). Developing views of nature of science in an authentic context: An explicit approach to bridging the gap between nature of science and scientific inquiry. *Science Education, 88*(4), 610–645.

Tsybulsky, D. (2013). *The effect of educational field trips to university research labs on students' understanding of the nature of science and attitudes towards science*. PhD thesis. The Hebrew University of Jerusalem.

Tsybulsky, D. (2018). Comparing the impact of two science-as-inquiry methods on the NOS understanding of high-school biology students. *Science & Education, 27*(7), 661–683. https://doi.org/10.1007/s11191-018-0001-0.

Tsybulsky, D., Dodick, J., & Camhi, J. (2012). *The effect of educational field trips to professional research labs on Students' understanding of NOS*. Indianapolis: A paper for the Annual Meeting of NARST.

Tsybulsky, D., Dodick, J., & Camhi, J. (2017a). The effect of field trips to university research labs on Israeli high school students' NOS understanding. *Research in Science Education.* https://doi.org/10.1007/s11165-016-9601-3.

Tsybulsky, D., Dodick, J., & Camhi, J. (2017b). High-school students in university research labs? Implementing an outreach model based on the 'science as inquiry' approach. *Journal of Biological Education, 52*(4), 415–428. https://doi.org/10.1080/00219266.2017.1403360.

Wilson, E.O. (2010). Within One Cubic Foot. *National geographic*. February and available at: http://ngm.nationalgeographic.com/2010/02/cubic-foot/wilson-text

Yarden, A., Brill, G., & Falk, H. (2001). Primary literature as a basis for a high-school biology curriculum. *Journal of Biological Education, 35*(4), 190–195.

Chapter 37
Strengthening Future Science Teachers' Understanding of Nature of Science: The Role of an Embedded Research Experience in Teacher Preparation

Julie Angle

Creating a scientifically literate populace has among many goals a desire for all students to have learning experiences that provide them with appropriate views of how science is conducted and how scientific knowledge is generated. Therefore, future science teachers should be equipped with the knowledge and skills to help reach that goal. Preparing individuals to become science teachers looks different depending on the path taken or the nature of their preservice program (Olson et al. 2015). Despite having a diverse array of licenses, requirements, and degree programs, the seriousness of the challenge of producing highly qualified science teachers is one widely shared by all those with a stake in the future of K–12 science instruction (NAS 2007; NRC 2010). This chapter discusses the development of a science methods course designed to provide preservice science teachers (PSTs) with a learning environment to strengthen three components of science literacy: science content knowledge, the methods/practices of science, and nature of science (NOS). To provide a strong context, I will discuss all three elements as they relate to the new science methods course but focus most strongly on NOS aspects that have shown much promise.

37.1 Rationales and Key Elements for a New Science Methods Course

To produce science teachers who are knowledgeable in how to teach their science content, like most teacher preparation programs, our university offers classes in the pedagogy of science. But, on reflection, it seemed that our PSTs lacked an

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_37

understanding of how science is conducted and how scientific knowledge is generated. Using best practices learned about research apprenticeships for high school, college and Research Experience for Teachers (RET) programs, explicit and reflective practices, and current expectations of the standards for science teacher preparation (NSTA 2012), we developed a course called S*cience Methods: Course-based Undergraduate Research Experience* (SM-CURE). SM-CURE includes three essential components including a research apprenticeship, explicit instruction, and reflective practices. The goal of the class is threefold, to (1) engage PSTs in a semester-long authentic research apprenticeship under the mentorship of science and engineering faculty, (2) provide PSTs with explicit-reflective instruction about nature of science, and (3) facilitate PSTs in transitioning their research into a standards-based research lesson that explicitly addresses scientific practices and NOS.

37.2 The Course Strategy Is Supported by Education Research

1. A science research apprenticeship is different from the science-learning environments familiar to most PSTs. Often, preservice teachers assume that science should be taught as a three-hour cookbook lab surrounded by 50-minute blocks of lecture because that is how they experienced science as students. To move away from stereotypic undergraduate science experiences, we designed a class that provides PSTs with a mentored research experience.

Research apprenticeships that provide opportunities for learners to work with practicing scientists on authentic scientific research are diverse in length, level of engagement, and desired outcomes (Baker and Keller 2010; Sadler et al. 2010). Nonetheless, the goal of most undergraduate science apprenticeships is to encourage participants to consider careers in science or remain in a science major (Hunter et al. 2007; Lopatto 2003, 2004; Russell et al. 2007). Additionally, there is growing evidence that engaging undergraduate students, including preservice science teachers, in a research apprenticeship results in a positive change in their understanding of science content (i.e., Burgin and Sadler 2016; Brown and Melear 2007; Hunter et al. 2007; Melear et al. 2000). The SM-CURE course leverages this type of learning experience, a science research apprenticeship, as a way to increase the number of future teachers who enter the classroom with a comprehensive understanding of how science is conducted and how scientific knowledge is generated. Additionally, the research apprenticeship is also used to teach about various aspects of nature of science through the lens of the research being conducted.

2. Research targeting the pedagogical practices of nature of science overwhelmingly favors an explicit instructional approach. Such an approach involves a strategically planned sequence of events to draw learners' attention to aspects of

NOS through a series of supports where learners are guided through the learning process, involving discussions and reflections related to the specific context of the activity or investigation (Duschl and Grandy 2012).

Learners do not automatically construct an understanding of NOS as a consequence of simply engaging in inquiry practices such as a research apprenticeship (Abd-El-Khalick and Lederman 2000; Bell et al. 2003; Lederman 1992). Some studies suggest that providing learners with a research experience in the absence of explicit NOS instruction fails to strengthen learners' views (Schwartz et al. 2004; Schwartz et al. 2010). Instead, learners must experience NOS through reflective practices to promote their understanding of and connections between inquiry practices and aspects of NOS such as the empirical, tentative, and theory-laden nature of science; the creative and imaginative nature of science, and the social and cultural embeddedness of science; as well as differences between observations and inferences, and scientific laws and theories (Abd-El-Khalick et al. 1998; Lederman 2007; Lederman and Abd-El-Khalick 1998; Lederman et al. 2002; McComas et al. 1998; Osborne et al. 2003; Schwartz et al. 2004). Thus, SM-CURE explicitly facilitates PSTs' understanding of and brings relevance to specific aspects of NOS through the lens of PSTs' research experience, class activities, and guided discussions.

3. Reflective practices (explicit and deliberate self-description of activities and outcomes and the rationale for them) are used in SM-CURE as a metacognitive tool that is particularly important when making connections between aspects of NOS to events taking place during PSTs' research apprenticeship. Melville and his colleagues demonstrated that oral and written reflections serve as mechanisms to facilitate PSTs' pedagogical growth and make their beliefs visible when given proper support and scaffolding (Melville et al. 2008). Facing challenging experiences, such as an authentic research experience, and constructively reflecting on those experiences help to develop a deeper understanding about NOS (Bell et al. 2003; Melville et al. 2008; Windschitl 2004). Therefore, SM-CURE provides PSTs with multiple opportunities to become increasingly familiar with important understandings about NOS through both oral and written reflections.

We are reminded that a single course may not be enough to provide a comprehensive learning environment to strengthen learners' views of NOS (i.e., Bell et al. 2000; Lederman, 1999). However, the research supporting each of the three key course elements (the research apprenticeship, explicit instruction about NOS, and reflective practices) provides us with confidence that the situated learning environment associated with SM-CURE is inclusive enough to, at a minimum, strengthen PSTs' understanding of how to implement aspects of nature of science into classroom practice. We consider SM-CURE as an emersion in learning about and relevance to nature of science, which is supported by the idea that PSTs learn how to connect authentic scientific practices with how scientific knowledge is generated. Additionally, PSTs' understanding of how to implement aspects of NOS into classroom practice is strengthened as they develop a research-based inquiry lesson that transitions their research into a middle school or high school classroom learning environment.

37.3 The Elements of a Successful SM-CURE

Encountering aspects of NOS within a research apprenticeship is a situated learning environment where learning takes place in the same context in which it is applied – in the laboratory or field. This inclusive situated learning environment generates a community of practice among the individuals who engage in the same collective learning process (Wenger 1998). During SM-CURE, PSTs work with a research mentor (i.e., a scientist or engineer) to conduct scientific or engineering research, participate in research-team meetings, design and present a research poster, write a scholarly manuscript (to be submitted to our university's online undergraduate research journal), and, as a culminating event, design a research-based lesson that allows the research experience to inform teaching practice. It should be clear that this lab/field research-based learning environment is very different from the way PSTs learn "about" science in their high school and college science courses.

37.3.1 Information Provided to PSTs During an Orientation Meeting

To establish a strong partnership between PSTs and research mentors, a required orientation meeting is held during the fall semester for the PSTs who plan to enroll in SM-CURE in the spring. This meeting occurs the semester before SM-CURE so that PSTs have ample time to find a research mentor before the end of the fall semester, meet the research team (including graduate students and staff), receive relevant reading materials and instructions essential to begin conducting research with a sound novice-level knowledge base, and establish a weekly research (work) schedule based on the availability of all involved with the research. This preplanning schedule positions PSTs to begin their research apprenticeship the first week of the SM-CURE course in the spring.

During the PST orientation meeting, we review course assignments and offer suggestions on how PSTs might find a research mentor. To begin the search for a research mentor, PSTs are encouraged to speak with their content course instructors or conduct an Internet search targeting the types of research taking place on the university campus. If a PST is unable to secure a mentor, names of faculty members who have either mentored PSTs previously or who have expressed interest in serving as a research mentor are provided.

37.3.2 Preparing the Research Mentors

Not surprisingly, most PSTs typically want to work with a research mentor in their science content field, but some are willing to branch out and work with STEM faculty (or graduate students) in fields that cross disciplines, such as bioengineering, animal meat sciences, and nutritional sciences. Irrespective of the field of study, under the leadership of their mentor, PSTs work in the lab or field assisting in experimental design, data collection and analysis, and drawing conclusions. Ultimately, the nature of the PST's involvement varies due to the timing of when the PST enters the ongoing research endeavor. Regardless, PSTs enter the research process and are actively involved in scientific practices well beyond what they would experience in a typical science lab course.

To ensure that the mentor-PST relationship is mutually beneficial, research mentors also participate in an informational meeting designed to explain the expectations of the experience and associated SM-CURE course requirements. Faculty who agree to mentor a PST acknowledge their willingness to provide a supportive-mentored research environment during the 64-hour research apprenticeship, assist their PST in constructing a research poster, provide guidance to the PST in writing their manuscript, attend the PST's research presentation at the *Preservice Science Teacher Research Symposium & Reception*, and submit an evaluation/assessment of their PST's efforts in conducting research. Providing mentors with SM-CURE course assignment expectations and due dates helps them identify a research project, or part of a project, that the PST can complete in the allotted one-semester timeframe.

Just because research mentors are immersed in conducting scientific research, we cannot assume that they personally have a clear understanding of the meaning of nature of science. We have learned that while most mentors are aware of some of the basic concepts of NOS, many have not made the connections between aspects of NOS to what is explicitly occurring in their research activities; even fewer are aware of how to help others to understand aspects of NOS as it relates to their research. Thus, during the initial meeting with mentors, we provide a brief "review" of the aspects of nature of science that are explicitly addressed during SM-CURE. For example, mentors know that science is socially and culturally embedded but will not likely have articulated this in terms of how this concept has impacted or is impacting research in general or their research specifically. Additionally, many mentors use scientific models as a tool to test or interpret the natural phenomena associated with their research but have never tried to explain the rationale behind modeling as a scientific tool to the general populace. Therefore, we inform mentors that as PSTs prepare to submit written reflections or engage in class discussions that explicitly address NOS, they may ask for help in making connections between their research experience and aspects of NOS. For example, PSTs often ask mentors about the scientific theories and laws associated with their research or how the knowledge base of their research has changed over the years. By informing mentors about the aspects of NOS emphasized in SM-CURE, these mentors are better equipped to address PSTs' potential NOS inquiries.

In addition to the initial mentor meeting, mentors receive bimonthly emails designed to remind them of PSTs' upcoming assignments associated with the research apprenticeship. These emails also provide mentors with a venue to communicate with the course instructor should any issues or concerns arise with the PST.

Table 37.1 SM-CURE assignments and due dates in a 16-week semester course

Assignments contributing to course grade	Approximate due date
Flinn scientific online safety training	Week 4
The Immortal Life of Henrietta Lacks reading	Week 8
Support staff for the regional junior science and humanities symposium (JSHS)	Week 9
∗Middle/high school research-based lesson plan	Week 13
∗Research manuscript	Week 14
∗Research journaling notebook	Week 14
∗Research apprenticeship, minimum of 64 hours	3–5 hours/week for 15 weeks
∗Research poster and presentation at the PST Research Symposium & Reception	Week 15
Mentor evaluation of PST	Week 15
∗Written reflections	Four throughout semester
SM-CURE attendance and class participation	Weekly

37.4 SM-CURE Course Assignments

SM-CURE assignments are designed to engage PSTs in the authentic practices of science coupled with explicit-reflective instruction about NOS. Although many of the course assignments associated with the research apprenticeship are due at the end of the semester, the remaining SM-CURE assignments are turned in at various times earlier. Table 37.1 lists all SM-CURE assignments and due dates. Assignments that pertain specifically to the research apprenticeship or the learning aspects of nature of science are marked with an asterisk and will be discussed in detail subsequently.

37.5 Description of SM-CURE Assignments as they Relate to NOS Learning

During SM-CURE, preservice teachers learn many things that improve their scientific literacy skills (science content knowledge, knowledge of the methods/practices of science, and nature of science). While Table 37.1 lists all course assignments, this next section describes course assignments specifically implemented to strengthen PSTs' understanding of aspects of NOS, as well as increase their awareness of how to implement these aspects into the K–12 classroom.

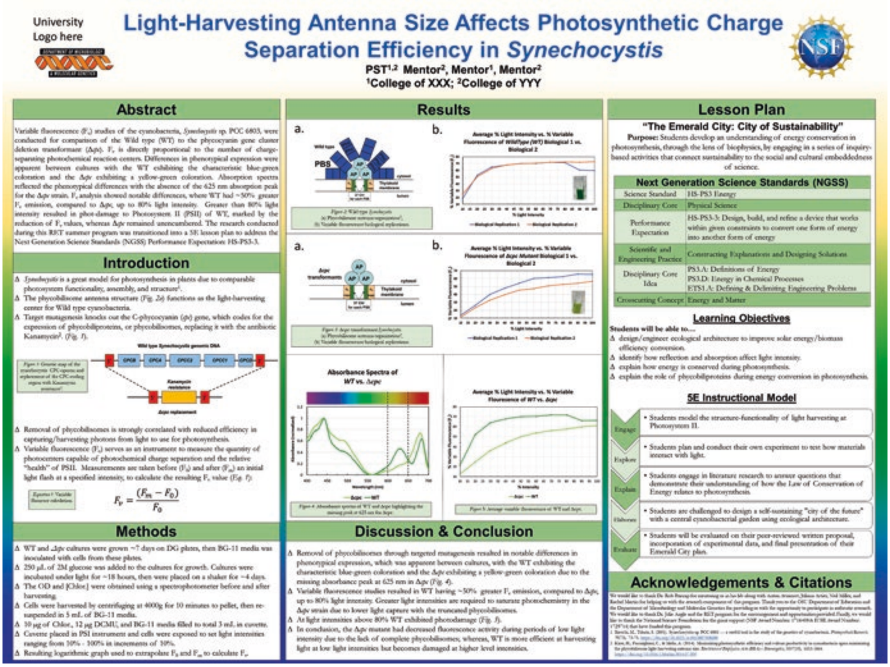
37.5.1 Research Apprenticeships in Support of NOS Learning

The *National Science Education Standards* (NRC 1996) and newer *A Framework for K–12 Science Education* (NRC 2012) suggest that teachers of science should teach science through the lens of scientific practices. These documents take the position that a research-based learning environment provides students with opportunities to engage in the same practices as that of science researchers. Thus, if future teachers of science are expected to teach science through the pedagogy of research, they should also have opportunities to engage in these same practices before entering the classroom.

For most PSTs, the research apprenticeship is the first time they have experienced authentic scientific practices without the "cookbook" science so typically included in lab classes. To provide PSTs with maximum time in the authentic research environment, under the constraints of a one semester 4-hour college course, PSTs begin their research apprenticeship the first week of SM-CURE and conclude when they present their research at the *Preservice Science Teacher Research Symposium & Reception*, at the end of the semester. Time spent investigating a specific topic advances PSTs' understanding of a science content and the practices associated with science research, beyond what they would experience without the apprenticeship program. In their review of research apprenticeships, Saddler et al. (2010) identified studies that suggested, under an explicit and reflective learning environment, a research apprenticeship has been shown to increase learners' understanding about NOS. We have noted that this explicit and reflective NOS learning occurs in SM-CURE. Through dialogue with their research mentors and the SM-CURE instructor, PSTs learn about the empirical NOS as data are generated but also learn that conducting science is a human endeavor that involves creativity beyond what they initially imagined, is impacted by funding, and is subjective and under peer scrutiny. To further augment the research learning experience through an explicit approach, during SM-CURE class meetings, PSTs engage in group discussions (small group and whole class) and submit written reflections, both of which focus on aspects of nature of science relating to their research apprenticeship (see Table 37.1).

37.5.2 Research Posters and Their Role in NOS Learning

After the conclusion of the apprenticeship, these preservice teachers develop a poster that describes their research. Posters display information typically found (abstract, introduction, methods, results, conclusions, references), but they also include a lesson plan summary (see Fig. 37.1) that is linked to state and national K–12 science standards. Strengthening their understanding of NOS, PSTs display the creative and imaginative methods used in their research, the empirical data collected, and conclusions drawn based on the evidence.



Light-Harvesting Antenna Size Affects Photosynthetic Charge Separation Efficiency in *Synechocystis*

PST[1,2] Mentor[2], Mentor[1], Mentor[2]
[1]College of XXX; [2]College of YYY

Abstract

Variable fluorescence (F_v) studies of the cyanobacteria, *Synechocystis* sp. PCC 6803, were conducted for comparison of the Wild type (WT) to the phycocyanin gene cluster deletion transformant (Δ*cpc*). F_v is directly proportional to the number of charge-separating photochemical reaction centers. Differences in phenotypical expression were apparent between cultures with the WT exhibiting the characteristic blue-green coloration and the Δ*cpc* exhibiting a yellow-green coloration. Absorption spectra reflected the phenotypical differences with the absence of the 625 nm absorption peak for the Δ*cpc* strain. F_v analysis showed notable differences, where WT had ~50% greater F_v emission, compared to Δ*cpc*, up to 80% light intensity. Greater than 80% light intensity resulted in phot-damage to Photosystem II (PSII) of WT, marked by the reduction of F_v values, whereas Δ*cpc* remained unencumbered. The research conducted during this RET summer program was transitioned into a 5E lesson plan to address the Next Generation Science Standards (NGSS) Performance Expectation: HS-PS3-3.

Introduction

Δ *Synechocystis* is a great model for photosynthesis in plants due to comparable photosystem functionality, assembly, and structure[1].
Δ The phycobilisome antenna structure (Fig. 2a) functions as the light-harvesting center for Wild type cyanobacteria.
Δ Target mutagenesis knocks out the C-phycocyanin (*cpc*) gene, which codes for the expression of phycobiliproteins, or phycobilisomes, replacing it with the antibiotic Kanamycin[2]. (Fig. 1).
Δ Removal of phycobilisomes is strongly correlated with reduced efficiency in capturing/harvesting photons from light to use for photosynthesis.
Δ Variable fluorescence (F_v) serves as an instrument to measure the quantity of photocenters capable of photochemical charge separation and the relative "health" of PSII. Measurements are taken before (F_0) and after (F_m) an initial light flash at a specified intensity, to calculate the resulting F_v value (Eq. 1).

$$F_v = \frac{(F_m - F_0)}{F_0}$$

Methods

Δ WT and Δ*cpc* cultures were grown ~7 days on DG plates, then BG-11 media was inoculated with cells from these plates.
Δ 250 μL of 2M glucose was added to the cultures for growth. Cultures were incubated under light for ~18 hours, then were placed on a shaker for ~4 days.
Δ The OD and [Chlor.] were obtained using a spectrophotometer before and after harvesting.
Δ Cells were harvested by centrifuging at 4000g for 10 minutes to pellet, then re-suspended in 5 mL of BG-11 media.
Δ 10 μg of Chlor., 12 μg DCMU, and BG-11 media filled to total 3 mL in cuvette.
Δ Cuvette placed in PSI instrument and cells were exposed to set light intensities ranging from 10% - 100% in increments of 10%.
Δ Resulting logarithmic graph used to extrapolate F_0 and F_m to calculate F_v.

Results

Discussion & Conclusion

Δ Removal of phycobilisomes through targeted mutagenesis resulted in notable differences in phenotypical expression, which was apparent between cultures, with the WT exhibiting the characteristic blue-green coloration and the Δ*cpc* exhibiting a yellow-green coloration due to the missing absorbance peak at 625 nm in Δ*cpc* (Fig. 4).
Δ Variable fluorescence studies resulted in WT having ~50% greater F_v emission, compared to Δ*cpc*, up to 80% light intensity. Greater light intensities are required to saturate photochemistry in the Δ*cpc* strain due to lower light capture with the truncated phycobilisomes.
Δ At light intensities above 80% WT exhibited photodamage (Fig. 5).
Δ In conclusion, the Δ*cpc* mutant had decreased fluorescence activity during periods of low light intensity due to the lack of complete phycobilisomes; whereas, WT is more efficient at harvesting light at low light intensities but becomes damaged at higher level intensities.

Lesson Plan

"The Emerald City: City of Sustainability"

Purpose: Students develop an understanding of energy conservation in photosynthesis, through the lens of biophysics, by engaging in a series of inquiry-based activities that connect sustainability to the social and cultural embeddedness of science.

Next Generation Science Standards (NGSS)	
Science Standard	HS-PS3 Energy
Disciplinary Core	Physical Science
Performance Expectation	HS-PS3-3: Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy
Scientific and Engineering Practice	Constructing Explanations and Designing Solutions
Disciplinary Core Idea	PS3.A: Definitions of Energy PS3.D: Energy in Chemical Processes ETS1.A: Defining & Delimiting Engineering Problems
Crosscutting Concept	Energy and Matter

Learning Objectives

Students will be able to…
Δ design/engineer ecological architecture to improve solar energy/biomass efficiency conversion.
Δ identify how reflection and absorption affect light intensity.
Δ explain how energy is conserved during photosynthesis.
Δ explain the role of phycobiliproteins during energy conversion in photosynthesis.

5E Instructional Model

- Students model the structure-functionality of light harvesting at Photosystem II.
- Students plan and conduct their own experiment to test how materials interact with light.
- Students engage in literature research to answer questions that demonstrate their understanding of how the Law of Conservation of Energy relates to photosynthesis.
- Students are challenged to design a self-sustaining "city of the future" with a central cyanobacterial garden using ecological architecture.
- Students will be evaluated on their peer-reviewed written proposal, incorporation of experimental data, and final presentation of their Emerald City plan.

Acknowledgements & Citations

Fig. 37.1 Example of a preservice science teacher's research poster. In addition to the typical information found in a research poster (abstract, introduction, methods, results, etc.), the PST research poster contains a summary of the standards-based lesson that is developed through the lens of the research conducted

Class time is not provided to construct posters, but is used to address PSTs' questions and engage in a peer review, which is included in the course to simulate the peer review process scientists go through when submitting their research for consideration in journals or conference presentations. Because science is a human endeavor, PSTs learn that peer review is a vital mechanism used to minimize potential biases in science. PSTs share the progress made on their poster beginning week nine in the semester. As PSTs review posters, they learn about the methods and practices of scientific research so different from the research they are conducting. This review process also strengthens PSTs' understanding that there is not just one scientific method, often taught in school.

37.5.3 *Preservice Science Teacher Research Symposium & Reception*

A component of SM-CURE is that PSTs present their research during the *Preservice Science Teacher Research Symposium & Reception*. This event highlights research conducted by PSTs under the mentorship of STEM faculty. Administrators, faculty,

Table 37.2 Selected recent research poster titles, research focus, and hosting department/school

Poster title	PST research focus	Department/school of research mentor
Hard mast production and food availability for the Oklahoma black bear	Collected and measured food (fruits, berries, acorns, and nuts) availability for Oklahoma black bears	Department of Natural Resource Ecology and Management
High-yield secretion of multiple client proteins in *Aspergillus*	Examined the effect of maltose-induced overexpression in *Aspergillus*	Department of Microbiology
Disease avoidance behaviors of Zebra finches	Analyzed avoidance behaviors of healthy birds over sick birds	Department of Integrative Biology
Effects of light intensity on growth patterns in *Setaria viridis*	Analyzed C4 grass, *Setaria viridis*, to determine effects that light intensities have on phenotypes at plant maturity	Department of Plant Biology, Ecology & Evolution
Grouping patterns of upside-down *Cassiopea medusa*, jellyfish	Developed an experimental protocol to characterize grouping behavior of *Cassiopea medusa*	School of Mechanical and Aerospace Engineering
Identifying morphologies of trypanosomes in *Rana sphenocephala*	Identified species of trypanosomes found in southern leopard frogs (*Rana sphenocephala*)	Department of Integrative Biology

and graduate and undergraduate students from across campus often attend this one-hour come-and-go event during which PSTs discuss their research with attendees. Conducting research and then presenting it to an audience further enforce that science is a human endeavor that is influenced by social and cultural elements, and that others in similar science fields may have evidence to support differing views.

During the *Symposium*, we show a continuous slideshow presentation of photos of the research mentors to acknowledge them to their peers and administrators and to encourage future participation in the PST research apprenticeship program. Table 37.2 provides examples of PSTs' research titles, research focus, and the department/school of their research mentor.

Even though many of our PSTs are in biology, students often discover the crossover and relatedness of disciplines by working in laboratories other than those specifically in biology. This crossover of disciplines and colleges has helped PSTs to develop a better understanding that research does not occur in a silo but draws on many disciplines with multiple commonalities (Bybee 2014; NGSS Lead States 2013).

37.5.4 The Research Paper

Writing is a vital tool in communicating research findings (Cook and Dinkins 2015); therefore, PSTs submit a 5–6-page research paper (manuscript) that strongly resembles, on a smaller scale, one that would be submitted for publication in a scientific journal. This paper includes more in-depth information than is listed on the research poster. It also provides a more thorough description of the middle or high school science lesson that was developed to reflect the research. Few PSTs have conducted authentic scientific research, and even fewer have written a scientific manuscript; thus, this experience can be a daunting task. To facilitate writing the manuscript, PSTs receive guidance throughout the semester from the SM-CURE course instructor and their research mentor. To encourage PSTs to read related literature, PSTs submit literature reviews in response to writing prompts in their first three written reflections (see Table 37.1).

The preparation of a manuscript offers a unique experience to make a direct link to the social character of knowledge construction in science and the important role of review by experts within the research community. This review process is used to scrutinize knowledge claims and to ensure accountability and commitment to shared criteria. Thus, to simulate the peer review process in science, upon submitting their manuscript, PSTs receive comments from a blind peer review process (we seek out graduate students in related fields of study). If the reviewers think that the manuscript has merit, PSTs have an opportunity to make revisions and resubmit it in anticipation of it being accepted to our online journal for undergraduate research supported by our university. Writing the manuscript and submitting it for blind review further strengthens PSTs' understanding of how the research apprenticeship replicates how scientific knowledge is generated. This writing assignment is a concept of "science" that most PSTs never experience until they engage in this research apprenticeship.

37.5.5 Preparation of a Standards-Based Research Lesson

PSTs are tasked with developing a research-based lesson that can transfer what they learned during their research apprenticeship into an appropriate middle or high school science lesson that has a research focus. One goal of this lesson is to teach PSTs how to design lessons that engage students in the scientific practices of authentic research. A second goal is to facilitate PSTs' understanding of how to engage their future students in the practices of science through the lens of nature of science. Bell et al. (2000) demonstrated that just learning about NOS provides no guarantee that a teacher will incorporate aspects of NOS into classroom practice. Thus, the lesson plan template requires one of the lesson's learning objectives to address one or more aspects of NOS. With each identified aspect of NOS, the PST provides a rationale for how it is explicitly addressed in the lesson, what the teacher is doing/saying to bring NOS to the attention of students, and what students should do/say when learning about the identified aspect of NOS. Table 37.3 provides examples of PSTs' research, the lesson developed to reflect the research, the instructional standard, and the NOS aspect(s) explicitly addressed in the lesson. Providing explicit attention to the inclusion of NOS in the lesson has reinforced PSTs' understanding of how to clearly implement NOS into their future science classroom curricula.

Table 37.3 Middle school and high school lessons developed from transitioning PSTs' research into classroom practice

Research poster title	Lesson title	Instructional standard from the US Next Generation Science Standards	NOS tenet(s) addressed in the lesson
Influences of disrupted genomic imprinting on maternal Care in Mice with interspecific offspring	Maternal behavior and offspring success in mice	HS-LS4 biological evolution: Unity and Diversity	Empirical; inferential
Transgenerational responses of freshwater snails to fish predation	Escargot, Escargoing, Escar-gone!	HS-LS2 interdependent relationships in ecosystems	Empirical
Building better liquids with structure property relationships and mixed molecular simulations	Molecular geometry: It keeps you in shape	HS-PS1 matter and its interactions	Creative and imaginative
Winter bat activity in relation to daily temperature, precipitation, and moon phase in Oklahoma	Getting batty with ecosystems	HS-LS2 ecosystems: Interactions, energy, and dynamics	Inferential; role of scientific models
Effects of diets on senescence in *Drosophila hydei*	Diets and ecosystems	MS-LS2 ecosystems: Interactions, energy, and dynamics	Inferential; role of scientific models
Monarch larvae and Fly parasitoid interactions: Progeny per host influences Fly body size	Effect of resource availability on population growth of house flies	MS-LS2 ecosystems: Interactions, energy, and dynamics	Empirical; role of scientific models; creative and imaginative

An external benefit of developing a lesson that transitions current research into practice is that it provides research mentors with a mechanism for disseminating their research to a broader audience by posting the lesson to their website as an open source document. Our research mentors receive no financial compensation for mentoring a PST; thus, allowing mentors to post their PST's lesson plan and research poster on their website validates their efforts of broader impacts to their department heads and potential funding agencies.

37.5.6 Fostering Explicit-Reflective Instruction About NOS

With the course overview in mind, we can now turn our attention to how NOS is explicitly and reflectively included in SM-CURE. An explicit and reflective method of instruction pertaining to NOS is defined as an "… approach [that] emphasizes student awareness of certain NOS aspects in relation to the science-based activities in which they are engaged, and student reflection on these activities from within a framework comprising these NOS aspects" (Khishfe and Abd-El-Khalick 2002, p. 555). In SM-CURE, reflective activities are conducted through two mechanisms: individual written reflections and class discussions.

Written Reflections in Support of NOS Learning Through Journaling PSTs maintain a journal that captures the "what," "when," "how," and "why" encountered during their research apprenticeship. Journaling in real-time is used as a mechanism to capture PSTs' ideas, thoughts, and questions generated as they engage in the practices of science (Wallace and Oliver 2003). Windschitl (2004) has shown that journaling is a way for PSTs to externalize self-dialogue about their research experience which would "normally be internal and poorly articulated, and to document this dialogue in a sharable artifact" (p. 487). Therefore, PSTs are instructed to make a note in their journal when something was said, or something was done that generated personal questions, reminded them of an aspect of NOS, or could be implemented into their lesson plan. Journaling is also used to record typical research information such as research methodology, data collected, tables and graphs generated, conclusions drawn, etc. Finally, PSTs use their written accounts as a "reminder-tool" to aid in their class discussions and in writing their reflections.

Written Reflections in Support of NOS Learning Through Responding to Writing Prompts To capture ideas generated during their mentored research apprenticeship and to make their research apprenticeship explicit objects of reflection, every 3–4 weeks, PSTs submit responses to 5–6 writing prompts. Table 37.4 lists reflective prompts that address the science content and practices associated with PSTs' research apprenticeship as well as writing prompts designed to address specific aspects of NOS, which are articulated through their research apprenticeship. The final writing prompt in each reflection is titled *Open Topic*. This section provides PSTs with an avenue to address topics that they want to share that is beyond the scope of the guided writing prompts. PSTs often use this section to address the highs/lows of their research experience, unexpected findings, questions they have, or new opportunities encountered. Responses to writing prompts also serve as a tool to assist the course instructor with discussion topics for whole-class discussions.

37.5.7 NOS in Small Group and Whole Class Discussions

Learning about NOS is not an implicit action but a deliberate one that must be planned for as part of preservice science teachers' instructional practices (Abd-El-Khalick et al. 1998; Duschl and Grandy 2012). As mentioned above, research suggests that a teacher's level of understanding about NOS does not always equate to transitioning this knowledge into classroom practice (Abd-El-Khalick et al. 1998; Abd-El-Khalick and Lederman 2000; Brickhouse 1990; Lederman 1992; Lederman and Zeidler 1987). We have found that helping preservice teachers become aware of

Table 37.4 Writing prompts for the SM-CURE written reflections

Reflection 1
Paint a descriptive picture of your research team
Pretend you are speaking to a group of middle or high school students; describe your research and its significance
Provide literature summaries of two research articles and explain how the research relates to the research you are conducting
Explain the experimental design of your study. What equipment are you using and why?
Explain how the "empirical NOS" relates to the research you are conducting
Open topic
Reflection 2
Identify obstacles you are experiencing in designing or executing your experimental design or in the data collection process. Explain how your experimental design has changed from reflection 1
Identify the quantitative and/or qualitative data you are collecting. How do you anticipate displaying these data to a broader audience?
Provide literature summaries of two research articles and explain how the research relates to the research you are conducting
Explain the driving scientific theories or scientific laws that support-explain-describe your research
Science is a human endeavor and thus contains social and cultural biases. Explain what/who is driving your area of research
Open topic
Reflection 3
Explain how you and your research team have used creativity and imagination in executing your research study
Explain the data you are collecting. Provide data tables with paragraph explanations for each data table/graph. What initial conclusions can you draw from the data you have collected?
Provide literature summaries of two research articles and explain how the research relates to the research you are conducting
What is a scientific model? What scientific model(s) is associated with your research? Explain how this model(s) has changed as your area of research has emerged
Do all researchers hold the same views about the research you are conducting – Why or why not?
Open topic
Reflection 4
As you write your manuscript and design your research poster, you have been asked to have it reviewed by your research mentor, research team, and SM-CURE peers. Explain the importance of peer review to the scientific community
Over the past 40 years, explain how scientists' understanding of your research has changed
List an observation you made as you collected data and an inference made based on your observation. Explain how your observation was different from your inference. How were they related?
Explain how peer review can limit scientific subjectivity
Open topic

their own NOS misconceptions better equips them to recognize aspects of NOS when they encounter it in the future. Thus, our strategy is to provide PSTs with reflective learning opportunities with the goal of increasing the likelihood of NOS being explicitly addressed when they enter their own classroom (Yacoubinan and BouJaoude 2010).

Research Apprenticeship and Reflective Group Discussions Peters and Kitsantas (2010) suggest that conceptual changes about NOS result through metacognition. Thus, each week, preservice teachers engage in whole class discussions to reflect on events linked to apprenticeships. Discussions focus on research methods, progress of data collection, obstacles encountered, research advances, etc. These discussions engage PSTs in reflective dialogue (Wenger 1998; Windschitl 2003) on aspects of NOS.For example, when PSTs discuss the empirical nature of science when asked about data collection as it relates to the natural phenomena they are investigating; the tentative yet durable nature of science when discussing how their research is different from yet based upon findings from prior studies; the theory-laden NOS when discussing the subjective and objective nature of their research; or the social and cultural aspects of science as they discuss the political, economic, and personal backgrounds that influence the direction of their research.

In-Class Activities and Reflective Group Discussions During SM-CURE, preservice teachers participate in class activities to further strengthen their understanding about NOS (Akerson et al. 2000). Each class activity focuses on one or more aspects of NOS. During an activity, PSTs work in small groups and engage in discussion. After the activity is completed, the whole class engages in a discussion and identifies aspects of NOS the activity addressed, what they learned as a result of engaging in the activity, and how the activity could be implemented into a middle school or high school classroom. Table 37.5 provides five examples that PSTs (now in-service science teachers) identify as activities they incorporate most often in their science classroom. While there is no particular order that the activities should be introduced, we introduce the “Potato Candle” activity because PSTs initially think that the goal of the activity is to review terms such as qualitative and quantitative. In reality, this discrepant event immediately addresses misconceptions that PSTs have regarding differences between observations and the social and cultural biases associated with the subjective nature of inferences.

After each activity, PSTs engage in reflective discussions, which are used to address misconceptions they may hold about the aspects of NOS as it relates to each activity (Schwartz et al. 2004). Group discussions build confidence in their pedagogy skills when PSTs reflect on what each activity could potentially “look like” in their future middle school or high school classroom. Discussions also support PSTs with addressing potential questions that their future students may have regarding NOS (Webb and Treagust 2006). Each activity is purposefully selected, not only for how it addresses various aspects of NOS but also for its low cost and simplicity to

Table 37.5 Examples of activities used to engage PSTs in explicit-reflective discussions about nature of science

Activity	Description of NOS activity	Aspects of NOS addressed
Potato Candle activity (Bell 2008)	The course instructor asks PSTs to make qualitative and quantitative observations about the object being held. The instructor writes PSTs' observations on the board and then asks, "based on your observations, what am I holding in my hand?" overwhelmingly, responses will be that the object is a candle… and then the instructor takes a bite of the object she is holding in her hand ∗the object held in the instructor's hand is a cored potato with a lit almond sliver as the "wick," but of course most students assume it to be wax candle	Inferential Theory laden
Cube activity (NAS 1998)	In teams, PSTs are provided with three paper cubes (one at a time). The first cube has a number on each side with some sides shaded. The bottom side of the cube is covered with an index card, and the team is tasked with predicting what is on the bottom of the cube based on patterns of evidence from the sides they can see. The second cube has paired opposite sides that are the same color (red, blue, or white). Each side also contains a male or female name and two different numbers. Once again, in teams, PSTs are tasked with predicting what is on the bottom side of the cube using patterns of evidence obtained from the sides they can see. The third and final cube is blank with no colors, numbers, or words on any of the sides. This final cube tasks PST to design their own patterns to be shared with peers. Discussion includes patterns of evidence that they are observing in their research	Empirical Inferential Theory laden Creative and imaginative
Fossil Footprints (NAS 1998)	In teams, PSTs make observations of "fossil footprints" in a three-part picture. Using observations, PSTs construct a defensible hypothesis or explanation for events in each of the three geological positions. As additional sections of the picture are revealed, PSTs' hypotheses or explanations are revised	Empirical Inferential Theory laden Tentative Creative and imaginative
Checks Lab (Loundagin 1996)	Student teams have an envelope containing a series of personal bank checks. A few checks are removed at a time. Using the information provided on the checks, each team constructs a plausible story. As additional checks are removed from the envelope, revisions are made to the story to accommodate the new information. Because teams randomly remove checks from their envelope, teams may or may not hold the same information and therefore will likely induce different conclusions	Empirical Tentative Inferential Theory laden Creative and imaginative Social and cultural embeddedness

(continued)

Table 37.5 (continued)

Activity	Description of NOS activity	Aspects of NOS addressed
Magic Glue (Llewellyn 2013)	Conducted as a demonstration, the instructor asks a PST to cup his/her hands while the "magic glue" is poured into her hands. The instructor proceeds to dip an end of a rope into the PST's hands to "soak up" the magic glue. The rope is then placed into a nontransparent bottle (such as a dark wine bottle) and unassumingly inverts the bottle. Unknown to the audience, resting at the bottom of the bottle is a rubber stopper. When the bottle is inverted, the rubber stopper traps the rope in the neck of the bottle allowing the instructor to swing the bottle from the rope. As the instructor puts the bottle upright again, she inconspicuously sticks a finger into the neck of the bottle to release the stopper, which releases the rope. PSTs are asked to draw a model that illustrates what is happening inside the bottle to explain the phenomenon	Inferential Theory laden Role of scientific models Creative and imaginative

implement into the classroom. Finally, group discussions address the ease with which teachers can explicitly teach about nature of science in a timeframe conducive to most secondary classrooms.

37.6 Changes in the Views PSTs Hold About Nature of Science

To measure changes in PSTs' views of nature of science, the Views of Nature of Science (VNOS-D) instrument is used because of the general nature of the questions (Lederman and Khishfe 2002). Using a five-level scoring index with "1″ representing a Naïve understanding, "3″ representing a Transitioning understanding, and a score of "5″ to represent a Well-Informed understanding, PSTs traditionally enter SM-CURE holding Naïve views of NOS. Typical views held by PSTs about NOS at the start of the semester include views such as *science is the study of everything*; *scientific knowledge changes whenever a scientist has a new idea*; *scientists have different views about things because if they were not around to see it happen, then they can never really know for sure what actually happened*; *laws are theories that have been proven correct*; *scientists all use the same scientific method, but they may use their creativity and imagination when thinking about what questions to answer*; and *science is universal to eliminate bias*. Despite having completed a minimum of 11 college science courses, with consistency, PSTs enter SM-CURE holding Naïve views of most aspects of NOS.

By the end of the SM-CURE semester, PSTs demonstrate views of NOS that support Transitioning or Well-Informed views of NOS. For example, PSTs suggest that *science is the study of the natural world and scientific knowledge is based on* *empirical evidence*; *scientific knowledge can change with new evidence or if technology allows us to observe phenomena that scientists did not know before*; *scientists may have different explanations … because they have different background experiences such as their content area, gender, political views, years of experience, and religious beliefs*; *scientific theories are used to explain and predict natural phenomena, and laws are descriptions of natural phenomena usually in the form of a mathematical equation*; and *science is a human endeavor so it will be influenced by the scientist's interests, political identity, religious values, gender, and financial support*. These views represent an understanding of NOS that better parallels NOS knowledge of what individuals should know (i.e., Abd-El-Khalick et al. 1998; Lederman et al. 2002).

Since we have implemented SM-CURE into the secondary science education degree program, significant gains in PSTs' understanding of all ten assessed NOS tenets have been reported. Over the past 4 years, 48 PSTs have entered SM-CURE with cumulative mean scores of 2.0, 2.2, and 2.2, on a scale of 1–5, for their understanding of the empirical NOS, the creative and imaginative NOS, and the social and cultural embeddedness of science, respectively. However, our PSTs enter SM-CURE holding an even lower understanding of scientific theories (1.3), scientific laws (1.8), the relationships between theories and laws (1.1), the role of scientific models (1.7), the tentative NOS (1.8), and the inferential NOS (1.9).

At the completion of SM-CURE, post-assessment scores show increases in PSTs' understanding of NOS. Over the past 4 years, post scores have ranged from 2.4 for PSTs' understanding of scientific laws to 3.6 for their understanding of the creative and imaginative NOS. While these scores are still straddling either side of the "Transitioning" level of understanding (on a scale of 1–5), all aspects assessed have shown significant increases.

An examination of pre/post responses reveals rich conceptual shifts in PSTs' understanding of key aspects about nature of science over the course of one semester. Several of the VNOS-D questions ask the learner to provide an example to support their response. Few pre-assessment responses included examples, or the responses included examples that did not correctly address the writing prompt. Interestingly, post-assessment responses often included examples that specifically relate to the research the PST conducted during the SM-CURE semester. This demonstrates an important connection between PSTs' research apprenticeship (how science is conducted) to their understanding of nature of science (how scientific knowledge is generated).

37.7 Conclusions

The National Science Teachers Association's position statement on nature of science states that "all those involved with science teaching and learning should have a common, accurate view of the nature of science" (NSTA 2000). Of course, such a goal is held by all of those who have contributed to this book. Thus, as science teacher educators, we feel that the logical point for equipping science teachers to teach with and about NOS starts with preservice science teachers during their teacher preparation program – before they enter the science teaching workforce. The National Association of Biology Teachers encourages teacher preparation programs to position PSTs to learn about NOS by providing "the preservice teacher with experiences that lead to an understanding of the nature of science" (NABT 2004). Schwartz et al. (2010) propose that immersion in a scientific research environment can result in positive changes in teachers' views of nature of science.

The strategies described in this chapter target the NOS learning gap of preservice science teachers through a unique pairing of a mentored research apprenticeship with explicit-reflective instruction about nature of science. We have strong evidence to suggest that providing PSTs with an environment where they learn about aspects of nature of science through the lens of a personal research experience coupled with explicit and reflective practices provides an increased understanding of NOS that is consistent with current education reform efforts (NRC 2012; NGSS Lead States 2013).

The uniqueness and success of the SM-CURE course is possible because our university is considered a research institution that recognizes the importance of providing undergraduates with a research experience. However, if PSTs are enrolled in a college or university where research is not emphasized, aspects of SM-CURE can still be addressed. Providing PSTs with explicit instruction about NOS through the many in-class activities and engaging them in discussions to bring metacognitive awareness to aspects of NOS can be done in alternative learning environments. Additionally, the course instructor could revisit the more traditional CURE model where all students are investigating aspects of the same research. Using the CURE model, all three essential components of SM-CURE can still be implemented: the research apprenticeship, explicit instruction, and reflective practices. And with modifications, the three course goals can also be achieved: (1) engage PSTs in a semester-long authentic research apprenticeship (as a class instead of individually), (2) provide PSTs with explicit-reflective instruction about nature of science (no modifications needed), and (3) facilitate PSTs in transforming their research into a standards-based research lesson that explicitly addresses scientific practices and NOS. This third course goal could be interesting since all PSTs conduct aspects of the same research; realistically, as a class, PSTs could develop an entire instructional unit around the same research.

We have found that immersing PSTs in a research-rich, explicit-reflective learning environment of SM-CURE results in significant changes in PSTs' understanding of NOS. Similar to Schwartz et al. (2004), we confirmed that learning about aspects of nature of science through a personal research experience provides applicability and increased understanding of NOS. However, contrary to the findings of Brown and Melear (2007), our PSTs not only successfully transition their research experience into classroom practice, but there is a knowledgeable effort to embed one or more aspects of NOS into the lesson they develop.

We have also found that unlike a typical CURE where all students in the class are engaged in aspects of the same research, PSTs in SM-CURE conduct authentic research under the guidance of a research mentor of their choice. This autonomy allows PSTs to work in research environments that are of value to their scientific interests and applicable to their future classroom curricula. And finally, similar to Pyle et al. (1997) who report that PSTs may feel more empowered to conduct authentic science research in their future classrooms as a result of their increased confidence acquired during their apprenticeship, we now have novice teachers implementing a science fair program at their school. These young science teachers are mentoring students in science research and coaching them in science fair competitions as early as their first or second year in the teaching profession.

References

Abd-El-Khalick, F., & Lederman, N. G. (2000). Improving science teachers' conceptions of nature of science: A critical review of the literature. *International Journal of Science Education, 22*(7), 665–701.

Abd-El-Khalick, F., Bell, R. L., & Lederman, N. G. (1998). The nature of science and instructional practice: Making the unnatural natural. *Science Education, 82*(4), 417–436.

Akerson, V. L., Abd-El-Khalick, F., & Lederman, N. G. (2000). Influence of a reflective explicit activity-based approach on elementary teachers' conception of nature of science. *Journal of Research in Science Teaching, 37*(4), 295–317.

Baker, W., & Keller, J. (2010). Science teacher and research (STAR) program: Strengthening STEM education through authentic research experiences for preservice and early career teachers. *Peer Review, 12*(2), 22–26.

Bell, R. (2008). *Teaching the nature of science through process skills: Activities for grades 3–8*. Boston: Pearson/Allyn and Bacon.

Bell, R. L., Lederman, N. G., & Abd-El-Khalick, F. (2000). Developing and acting upon one's conception of the nature of science: A follow-up study. *Journal of Research in Science Teaching, 37*(6), 563–581.

Bell, R. L., Blair, L. M., Crawford, B. A., & Lederman, N. G. (2003). Just do it? Impact of a science apprenticeship program on high school students' understandings of the nature of science and scientific inquiry. *Journal of Research in Science Teaching, 40*, 487–509.

Brickhouse, N. W. (1990). Teachers' beliefs about the nature of science and their relationship to classroom practice. *Journal of Teacher Education, 41*(3), 53–62.

Brown, S., & Melear, C. (2007). Preservice teachers' research experiences in scientists' laboratories. *Journal of Science Teacher Education, 18*, 573–597.

Burgin, S. R., & Sadler, T. D. (2016). Learning nature of science concepts through a research apprenticeship program: A comparative study of three approaches. *Journal of Research in Science Teaching, 53*(1), 31–59.

Bybee, R. W. (2014). NGSS and the next generation of science teachers. *Journal of Science Teacher Education, 25*(2), 211–221.

Cook, K. L., & Dinkins, E. G. (2015). Using popular text to develop inquiry projects: Supporting preservice teachers' knowledge of disciplinary literacy. *Journal of College Science Teaching, 44*(6), 44–50.

Duschl, R. A., & Grandy, R. (2012). Two views about explicitly teaching nature of science. *Science & Education*. https://doi.org/10.1007/s11191-012-9539-4. Retrieved from: http://www.bu.edu/hps-scied/files/2012/10/Duschl-HPS-Two-Views-on-Explicitly-Teaching-NoS.pdf.

Hunter, A. B., Laursen, S. L., & Seymour, E. (2007). Becoming a scientist: The role of undergraduate research in students' cognitive, personal, and professional development. *Science Education, 91*, 36–74.

Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus inquiry-oriented instruction on sixth graders' views of nature of science. *Journal of Research in Science Teaching, 39*, 551–578.

Lead States, N. G. S. S. (2013). *Next generation science standards: For states, by states*. Washington, DC: The National Academies Press.

Lederman, N. G. (1992). Students' and teachers' conceptions of the nature of science: A review of the research. *Journal of Research in Science Teaching, 29*(4), 331–359.

Lederman, N. B. (1999). Teachers' understanding of the nature of science and classroom practice: Factors that facilitate or impede the relationship. *Journal of Research in Science Teaching, 36*(8), 916–929.

Lederman, N. G. (2007). Nature of science: Past, present, and future. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 831–879). New York: Routledge Publishers.

Lederman, N. G., & Abd-El-Khalick, F. (1998). Avoiding de-natured science: Activities that promote understandings of the nature of science. In W. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 83–126). Dordrecht: Kluwer Academic.

Lederman, J. S., & Khishfe, R. (2002). *Views of nature of science, Form D*. Unpublished paper. Chicago: Illinois Institute of Technology, Chicago, IL.

Lederman, N. G., & Zeidler, D. L. (1987). Science teachers' conceptions of the nature of science: Do they really influence teacher behavior? *Science Education, 71*(5), 721–734.

Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., & Schwartz, R. S. (2002). Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching, 39*(6), 497–521.

Llewellyn, D. (2013). *Teaching high school science through inquiry and argumentation* (2nd ed.). Thousand Oaks: Corwin.

Lopatto, D. (2003). The essential features of undergraduate research. *Council on Undergraduate Research Quarterly, 24*, 139–142.

Lopatto, D. (2004). Survey of undergraduate research experiences (SURE): First findings. *Cell Biology Education, 3*, 270–277.

Loundagin, J. (1996). The checks lab. *Evolution and the Nature of Science Institutes*. Retrieved from http://www.indiana.edu/~ensiweb/lessons/chec.lab.html

McComas, W. F., Clough, M. P., & Almazroa, H. (1998). The role and character of the nature of science in science education. *Science & Education, 7*(6), 511–532.

Melear, C. T., Goodlaxson, J. D., Warne, T. R., & Hickok, L. G. (2000). Teaching preservice science teachers how to do science: Responses to the research experience. *Journal of Science Teacher Education, 11*(1), 77–90.

Melville, W., Fazio, X., Bartley, A., & Jones, D. (2008). Experience and reflection: Preservice science teachers' capacity for teaching inquiry. *Journal of Science Teacher Education, 19*, 477–494.

National Academy of Sciences. (1998). *Teaching about evolution and the nature of science*. Washington, DC: National Academy Press.

National Academy of Sciences, National Academy of Engineering, and Institute of Medicine. (2007). *Rising above the gathering storm: Energizing and employing America for a brighter economic future*. Committee on Prospering in the Global Economy of the 21st Century: An Agenda for American Science and Technology. Washington, DC: The National Academies Press.

National Association of Biology Teachers. (2004). *Biology teaching preparation standards for middle & secondary teachers – A position statement*. Retrieved from: http://www.nabt.org.

National Research Council. (1996). *National science education standards*. Washington, DC: The National Academy Press.

National Research Council. (2010). *Preparing teachers: Building evidence for sound policy*. Committee on the study of teacher preparation programs in the United States, Center for Education. Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press.

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts and core ideas*. Washington, DC: National Academies Press.

National Science Teachers Association. (2000). *NSTA position statement: The nature of science*. Retrieved from: http://www.nsta.org/about/positions/natureofscience.aspx.

National Science Teachers Association. (2012). 2012 NSTA standards for science teacher preparation. Retrieved from: http://www.nsta.org/preservice/

Olson, J. K., Tippett, C. D., Milford, T. M., Ohana, C., & Clough, M. P. (2015). Science teacher preparation in a north American context. *Journal of Science Teacher Education, 26*, 7–28. https://doi.org/10.1007/s10972-014-9417-9.

Osborne, J., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. (2003). What "ideas-about-science" should be taught in school science? A Delphi study of the expert community. *Journal of Research in Science Teaching, 40*(7), 692–720.

Peters, E., & Kitsantas, A. (2010). The effect of nature of science metacognitive prompts on science students' content and nature of science knowledge, metacognition, and self-regulatory efficacy. *School Science and Mathematics, 110*(8), 382–396.

Pyle, E. J., Obenauf, P., Heatherly, S. A., DiBiase, W., Hemler, D., Govett, A., Evans, J., & Gansneder, B. (1997, January). The impact of the teacher research experience: Learning "real" science in a "real" context. Paper presented at the meeting of the Association for the Education of Teachers in Science, Cincinnati, OH.

Russell, S. H., Hancock, M. P., & McCullough, J. (2007). The pipeline: Benefits of undergraduate research experiences. *Science, 316*, 548–549.

Sadler, T. D., Burgin, S., McKinney, L., & Ponjuan, L. (2010). Learning science through research apprenticeships: A critical review of the literature. *Journal of Research in Science Teaching, 47*(3), 235–256.

Schwartz, R. S., Lederman, N. G., & Crawford, B. A. (2004). Developing views of nature of science in an authentic context: An explicit approach to bridging the gap between nature of science and scientific inquiry. *Science Education, 88*(4), 610–645.

Schwartz, R. S., Westerlund, J. F., Garcia, D. M., & Taylor, T. A. (2010). The impact of full immersion scientific research experiences on teachers' views of the nature of science. *Electronic Journal of Science Education, 14*(1), 1–40.

Wallace, C. S., & Oliver, J. S. (2003). Journaling during a school-based secondary methods course: Exploring a route to teaching reflection. *Journal of Science Teacher Education, 14*(3), 161–176.

Webb, P., & Treagust, D. F. (2006). Using exploratory talk to enhance problem-solving and reasoning skills in grade-7 science classrooms. *Research in Science Education, 36*, 381–401. https://doi.org/10.1007/s11165-005-9011-4.

Wenger, E. (1998). *Communities of practice: Learning, meaning, and identity*. Cambridge: Cambridge University Press.

Windschitl, M. (2003). Inquiry projects in science teacher education: What can investigative experiences reveal about teacher thinking and eventual classroom practice? *Science Education, 87*(1), 112–143.

Windschitl, M. (2004). Folk theories of "inquiry:" how preservice teachers reproduce the discourse and practices of an atheoretical scientific method. *Journal of Research in Science Teaching, 41*(5), 481–512.

Yacoubinan, H., & BouJaoude, S. (2010). The effect of reflective discussions following inquiry-based laboratory activities on students' views of nature of science. *Journal of Research in Science Teaching, 47*(10), 1229–1252.

Chapter 38
Introducing the Human Elements of Science Through a Context-Rich Thematic Project

Lotta Leden and Lena Hansson

38.1 Introduction

This chapter will describe and discuss how nature of science (NOS), and especially human elements of science (such as creativity, subjectivity, and sociocultural factors), could be taught in the middle school science classroom. The discussion is based on the examples from two classrooms where human elements of science were introduced through a thematic project on the topic of "Sugar and Sweeteners."

To include human elements of science in the teaching means challenging frequent myths about science such as science being an entirely rational, objective, and value-free enterprise (McComas 1998). Making NOS a meaningful part of science teaching also means challenging strong school science traditions; however, teachers can sometimes find it challenging to overcome such challenges (Aikenhead 2006; Bartholomew et al. 2004; Leden et al. 2015).

Teachers often have concerns regarding their students' abilities to deal with abstract or controversial issues (Abd-El-Khalick et al. 1998; Aikenhead 2006; Brickhouse and Bodner 1992; Leden et al. 2015; Lederman 1995). Human elements of science, possibly with the exception for creative aspects, are commonly regarded as complex and thus even more difficult to teach than other NOS aspects (Akerson et al. 2011). They are therefore often suggested as more suitable for students in later school years. See however Farland-Smith and McComas (2009) for examples of how human aspects of science can be taught in a middle school context. The present chapter continues to challenge the notion of difficulty connected to the teaching of human elements of science, through describing how these elements were fruitfully introduced to 12-year-old students.

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_38

There is also a need for examples of what a highly contextualized NOS teaching could mean for this age group. This is related to an ongoing discussion in the research literature about the value of teaching NOS through contextualized or decontextualized activities (e.g., Bell et al. 2016). Arguments have been raised for both types of NOS teaching and for the benefits of moving back and forth along a continuum with varied degrees of contextualization (Clough 2006). Some scholars (e.g., Hodson 2009) discuss the possibility that highly contextualized NOS teaching could be even more challenging for teachers than decontextualized activities (e.g., black-box activities). On the other hand, it has been argued that contextualized tasks (through, for example, student inquiry, contemporary cases, and historical cases) due to their complexity and authenticity could provide more meaning (Allchin 2014; Hodson 2009) and a deeper understanding of NOS (Clough 2006). Furthermore, some studies have emphasized the benefits of learning to teach NOS *on the spur of the moment* in connection to the teaching of, for instance, science concepts and models (see, e.g., Hansson and Leden 2016; Herman et al. 2013; Nott and Wellington 1998).

Regrettably, there are few examples of successful, contextualized NOS teaching (especially for young students) that could provide inspiration for teachers and teacher educators. Detailed examples could serve to show that such teaching is possible. This chapter shares a contextualized NOS teaching experience that focused on the human elements of science through employing socio-scientific issues (SSI) and inquiry approaches.

More specifically, the chapter describes examples of the work of two middle-school teachers (school years 4–6; ages 10–12) who planned and implemented a teaching sequence on “Sugar and Sweeteners” with the purpose for teaching aspects of NOS in connection with other curricular goals, goals related to argumentation, concept development, inquiry, and decision-making abilities. The two teachers were part of a 3-year-long research project on NOS and NOS teaching (Leden et al. 2015, 2017). During the project, six teachers regularly met in focus groups that focused on NOS teaching. One part of the project was the teaching sequence described in this chapter. The involved teachers had not previously taught about the human elements of science explicitly, but took the opportunity to do so when they got a chance to collaborate with colleagues. The teaching sequence was jointly planned by the teachers – they chose the topic and activities and made all practical arrangements. The researcher’s part in the planning was merely to remind the teachers to plan for explicit NOS teaching. During the implementation, the researcher remained an observer and did not contribute to the teaching.

The teaching sequence was implemented in both classrooms in similar, although slightly different ways. In the following description, the focus will be on how, and what, specific NOS issues were highlighted. The intent here is not to describe everything, but to contribute examples of what we consider to have been interesting issues and fruitful ways to approach NOS. We also comment on some instances where issues could have been discussed, even if this did not happen in the particular cases described here. The description of the teaching examples is based on field notes made by the first author during classroom observations. The examples show that many NOS issues were addressed, some of which were planned beforehand and others were addressed because of questions and discussions initiated by the students.

38.2 A Thematic Project on the Topic of Sugar and Sweeteners

The overall focus for the teaching sequence dealt with the use of sugar versus other sweeteners. The teaching sequence was highly contextualized in more than one way. First, it was closely connected to science content (chemistry and biology) that dealt with carbohydrates and other substances (see Sect. 38.2.1), as well as bodily functions and diseases. Second, NOS was discussed in the context of inquiry. Third, it was contextualized through its relationship to ongoing debates in media[1] and society concerning personal choices and societal recommendations and regulations related to benefits and risks of using sugar or sweeteners in different products. The topic of "Sugar and Sweeteners" can be characterized as ongoing research – the research community has not yet reached consensus on a general picture of benefits and risks in relation to health and environment. Hence, the topic differs from common science class topics, which mostly deal with science where consensus has been reached long ago.

As previously mentioned, the NOS focus for this unit was to increase students' awareness of the influence of human elements of science as well as to develop their abilities in relation to other curricular goals. The teachers decided that this should be accomplished through taking a starting point in their students reading of news articles and information from websites about sugar and sweeteners. The readings were selected by the teachers. The reading and discussions of the articles/websites served as a basis both for a debate and a student-led investigation on the topic. During the teaching sequence, teachers were careful not to provide right answers or specific statements about NOS, but instead initiate reflective discussions among the students. Thus, as suggested in Clough (2006, 2011), the discussions were the starting point for student reflection. In addition to the planned NOS issues, there were also several NOS issues raised in the classroom that had not been planned beforehand (including also NOS aspects other than human elements, such as the empirical and tentative nature of science). Thus, the teachers seized the moment and focused students' attention on relevant NOS issues through, for instance, asking questions. The different NOS issues, related to human aspects of science, that were raised during the teaching sequence included:

- *Creativity* impacts the choices of problems to investigate, procedures, and findings.

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[1] Examples of documentary movies are "Sugar Coated," "Fed Up," and "The Sugar Film." Numerous articles in daily newspapers can also be found. Search for "Sugar" or "Sweeteners" on the Internet. See also footnote 2.

- *Controversies and ongoing debates* within the research community.
- Impact of *preconceptions*, *values*, *and bias* on research processes.
- *Trustworthiness* related to media and researchers' investigations.
- *Economic aspects* can affect research (through, for example, funding).
- *Interrelatedness with society* regarding health regulations, environment, and Western/non-Western perspectives.
- The role of *communication*, *argumentation*, *and collaboration* for establishing results or conducting robust investigations.

In the following sections of this chapter, the NOS issues are discussed in greater detail with respect to the different parts of the teaching sequence. To understand where in the unit each of the NOS issues was raised, see Table 38.1. This table illustrates how multiple connections were made to each issue through different parts of the teaching sequence, thus strengthening students learning of how the human elements of science are interconnected. Depending on students' previous experience, the time spent on and the support in different parts of the project have to be adapted. For clarity, the above NOS issues are highlighted in italics in each part.

38.2.1 Introduction to the Thematic Project

The introductory session served to initiate discussions on some of the planned NOS issues, as well as a way to introduce relevant science content such as differences and similarities between different types of carbohydrates like sugar and starch, as well as the role of the photosynthesis for the production of sugar. This content became relevant for the students through asking questions such as the following: How does sugar become part of, for example, a strawberry? What is sugar used for in the human body? Are there carbohydrates in potatoes? Are there different kinds of sugar and sweeteners?

At the beginning of the thematic project, the students were asked to check at home for products that contained either sugar or sweeteners. The teacher also urged

Table 38.1 Summary of issues connected to human elements of science taught during different parts of the thematic project

	Part of teaching sequence			
Issue	Introduction	Reading	Debate	Investigation
Creativity	x			x
Controversies and ongoing debates	x	x	x	
Preconceptions, values, and bias	x	x	x	x
Trustworthiness	x	x	x	
Economic aspects		x	x	x
Interrelatedness with society		x	x	
Communication, argumentation, and collaboration			x	x

the students to try to find out a little bit more about sugar and sweeteners by using the Internet. The search for information introduced the students to the science content and gave them opportunity to realize that there could be contradictory research results as well as different views among researchers concerning the conclusions from different research studies. Furthermore, the influence of values and personal opinions among researchers as well as in the general public became clear (*controversies and ongoing debates* and *preconceptions, values, and bias*). Here, the role of media became an issue. Citizens often encounter research filtered through media. Thus, not only researchers' own bias and values are relevant, but also the journalists' preconceptions and values. The home investigation was followed by a teacher-led whole-class discussion where the students could share their findings and discuss if their findings were expected/unexpected and if different methods could be developed to find out more (*creativity*). Also discussions on the different ways that the students had gone about their investigations were included. Here it became clear that differing results among students could depend on different things including how the "data collection" was carried out – for example, did you choose to look in the pantry, in the refrigerator, or focus on the products that ended up on the kitchen table (*trustworthiness*)? Furthermore, they discussed the reasons for why different personal opinions emerge (influence from research results and/or other sources such as authority).

In summary, the NOS issues discussed during the introduction were creativity; controversies and ongoing debates; preconceptions, values, and bias; and trustworthiness. During this session, the parallels between students' own opinions, decision-making, or investigations and the work of researchers were often implicit rather than explicit discussions on the human elements of scientific research. However, explicit links could easily have been included through, for example, asking questions about researchers' work: How do researchers know if they have chosen a suitable way of investigating something? Do they use different approaches to learning new things? How come researchers do not always agree on interpretations or pros and cons with different research methods? In order to provide meaning to the introductory to the teaching sequence, explicit references to NOS can (and should) be made either during the session or in retrospect.

38.2.2 Reading and Discussing About the Sugar/Sweetener Debate

The teachers chose four articles/webpages for the students to read, two of which put forward arguments against sweeteners and two of which were pro sweeteners[2]. Similar to other media, the chosen articles/webpages refer to authentic research

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[2] The teachers mostly used Swedish news articles and webpages, but similar examples are available in English. Also other forms of media can be used, as, for example, documentary movies; see

studies and researchers in different ways and to various extents (see descriptions below). In this respect, the students experienced science as it can be in everyday life and as interested citizens. All four readings were edited and shortened to some extent by the teachers. Information about the readings is presented below:

- Online article from a well-known Swedish consumer magazine with price and product comparisons. The article begins by claiming that there is a growing interest in sweeteners that are free from calories. Two main reasons provided include: (a) that carbohydrates are connected to weight gain and (b) that the use of stevia was recently (2011) allowed in EU. The writer continues by claiming that despite careful control from EU, concerned voices have been raised about the use of stevia and other additives. A professor in medical and physiologic chemistry was interviewed and provided the reader with perspectives on the possibility that sweeteners can be the cause of, contrary to prevention of, weight gain.
- Online article from one of the largest daily newspapers in Sweden. The article refutes claims from an Italian study that aspartame can be the cause of cancer. The Italian study was performed on rats but rejected by the European Food Safety Authority (EFSA) which claimed that studies made on rats cannot be considered valid for humans. Thus, no new recommendations will be put forward. Also, the Swedish Food Agency has rejected the Italian study claiming that studies have been carried out for more than 25 years without showing any increased risks or negative effects on fertility or cancer with the exception for persons with the congenital disease phenylketonuria.
- Sports/food/health site on the Internet. It begins with a criticism of sensation-seeking press that claim to add fuel to a debate full of rumors and bias. It introduces the reader to the dangers of sugar with respect to obesity and a number of diseases. It continues by discussing sweeteners as an important alternative for people with diabetes or people who want to lose weight. This is followed by detailed information about aspartame: its contents, phenylketonuria, fears, and risks. Most risks are rejected due to the argument that research only has been performed on animals. It is also argued that there is a lack of research on other reported effects such as headaches and that results from questionnaire studies could be affected by the respondent’s values. In this web-based article, the writer presents his own interpretations of the research and refers to a number of research studies.
- “Lifestyle” page on the Internet. It targets the disadvantages of drinking a lot of diet soda. Referring to *American Journal of Clinical Nutrition*, this site claims that adolescents, during the last 10 years, have doubled their intake of diet soda. Six major disadvantages regarding diet soda are discussed: kidney problems, poor metabolism, obesity, cellular damage, rotting teeth, and fertility problems.

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footnote 1. It is however important when selecting the readings that different standpoints are shown which could be coupled to NOS.

The disadvantages are justified by references to specific investigations (described in some detail), or statements made by researchers.

The students worked in small groups and took turns reading aloud. The teachers used this approach as a way to facilitate the reading as well as promote discussions among the students. As a group, the students could support each other in highlighting important parts of the articles and in explaining meaning and specific words. Merely by reading the articles, the students could get an insight into that uncertainty and ongoing discussions characterize research, related to this topic (*controversies and ongoing debates*); that there can be a certain amount of bias involved (*preconceptions/bias*); that there could be certain purposes behind the reported research results; and that the validity and trustworthiness of research studies are important issues (*trustworthiness*). The teachers were, however, aware that students would need to explicitly reflect on these matters to gain a more robust understanding of the human elements of science. Thus, all groups were provided with a sheet of specific questions to focus on during their reading. These questions were prepared by the teachers in advance and contained questions which the teachers hoped would generate fruitful starting points for discussions related to human aspects of science. The questions were:

- Who (person/website) wrote/published this text?
- What is their message? Are they for or against sweeteners?
- For whom is the text written? (e.g., old/young, men/women, doctor/canteen personnel)
- Who has requested this research and does it matter?
- Why is this an area of investigation?
- Is this research interesting for everyone or is it only interesting for those in the western world?

The list includes questions dealing with the role of media and journalists, but also questions (the last three) directly related to human aspects of science. During students' reading, the teacher was a guide, picking up on discussions in the different groups and initiating new ones through asking questions, following up, and scaffolding the students in their discussions about the above questions (except for the last question which was saved for the whole class discussion). The teachers also had an important role in clarifying the science content; a great deal of new concepts that dealt with diseases, substances, and the human body were discussed.

The NOS-related questions above, as well as the science content, were further discussed in the whole-class discussion at the end of the sessions. During these discussions, the teacher focused on the questions in the list above. Moreover, they chose to emphasize certain other NOS issues that had been up for discussion in the small groups, so that all students would experience and have a say in these interesting topics (see the example of trustworthiness and different ways to conduct investigations described below). Some examples of issues that were highlighted are:

- *Preconceptions, values, and bias*. It was clear from the articles that there could be different opinions in the general public regarding sugar and sweeteners. It was also evident that many of the students had a quite clear opinion of their own before starting to read. This lead to a discussion about preconceptions: Could students' preconceptions affect what they thought about the contents of the articles? Do the values of the writer affect how research results are presented? Could researchers' preconceptions affect results or reports on results?[3]

- *Funding and other economic issues*. In a few of the readings, it was clear that EU was a large economic part in the research. This led to discussions about why this kind of research was interesting/important (e.g., concerns about peoples' health). In a couple of texts, it was less clear who had initiated the research, and the students were asked to think about that. They also discussed if the results could be affected by who funded the research. Could companies behind the research, such as diet soda companies, sometimes benefit economically from the research?
- *Trustworthiness*. How do we know what information to trust? Are there qualitative differences between the text sources? What do the different texts want the reader to think? Does it matter who is reporting on the research (writing the article) and does it matter who is behind the research? What can be said about how the research is conducted? Is it, for example, true that research made on animals cannot be trusted to say anything about the effects on humans? Thus, during the discussions, trustworthiness was related to different actors: media and researchers' investigations.
- *Western/non-Western research.* Here the students were urged to think about for whom it would be of most importance to think about health problems related to sugar and sweeteners and if all parts of the world would find this research equally important.

Thus, during this part of the teaching sequence, students first encountered human elements of science through the readings. These elements were then further explicitly reflected on in group and whole-class discussions where teachers encouraged their students to engage in the discussion through pondering deeply on different perspectives, putting forward their respective views, and putting new questions to each other.

38.2.3 Panel Debate

Students were asked to prepare to take part in a debate about sugar versus sweeteners. In the example here, a panel debate with an audience of younger students was organized. Another possibility could be to arrange debates between pairs or small student groups (with or without audience).

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[3] In connection to these discussions, it would also be valuable to, again, emphasize that this particular research area is characterized by differing interpretations, conclusions, and debates among researchers – features of ongoing research (controversies and ongoing debates).

Before the debate, the students decided on a certain position either for or against the use of sweeteners as a substitute for sugar. The students themselves decided what position to take (not all chose to argue in favor for their own personal position). This led to a discussion about preconceptions (students' own as well as researchers') and what these were formed by (*preconceptions, values, and bias*). The students were grouped together in accordance with their position. They collected arguments and justifications from the previously read articles and websites as well as from other resources. They also predicted and prepared for any counterarguments. Through this preparation, it became even clearer than before that different positions could exist in parallel, both of which were supported or underpinned by different lines of research (e.g., funded research by a governmental agency or research funded by soda or sugar companies) (*preconceptions, values, and bias; economic aspects*).

When they were confident in their preparations of the panel debate, an audience of younger peers (ages 10–11) was specifically invited as a way to render authenticity and importance to the session. The teacher acted as moderator during the discussion, and the audience members were called on to ask questions or make comments (*communication/argumentation/collaboration*). There was also an explicit discussion about purposes, interests, and trustworthiness behind the research that the respective group built their arguments on (*trustworthiness, economic aspects*). Environmental/societal impact connected to choosing either sugar or sweeteners was also discussed during the debate (*interrelatedness with society*).

After the debate, by the end of the session, the teacher once again gathered the students in a whole-group discussion where important components of a good argumentation were pinpointed (e.g., listening carefully to the arguments from the other side and replying to these arguments in a productive way; being prepared to justify their own arguments). This was also a good time to open up for discussion on some NOS issues that had only implicitly been touched upon during the argumentation. These NOS issues primarily dealt with controversies in science and how these can be dealt with through, for example, argumentation and communication among scientists (*communication/argumentation/collaboration*). That is, what do scientists or research groups do in reality when they do not agree on something?

Discussing the influence of researchers' personal preconceptions, values, etc., as well as theory ladenness is important but must not end up in communicating that "science is only opinions." Subjectivity in science has to be discussed in connection with how research is performed and scrutinized by the research community. Including human aspects of science in the teaching of science should thus not be a way to downgrade science, but a way to help students understand why researchers do not always agree concerning frontier science issues. This makes it possible to understand how science works which in turn might reduce the risk that students believe that science is only values.

38.2.4 Planning and Performing an Investigation (2 Sessions)

The students were asked to decide on a problem of interest to them concerned with sugar and sweeteners which they would be able to investigate empirically in the ordinary classroom setting. This generated interesting discussions about what kind of questions that are even possible to investigate scientifically which is connected to discussions about the limits of science. The students ended up with two investigations related to preferences and flavors. One idea was that it might be interesting to investigate if most people would prefer a soft drink sweetened with sugar or an artificial sweetener. Did preferences have anything to do with what they could actually taste? These students decided to ask people about their views on the topic before actually testing. The other idea was to investigate if people could taste if the same sort of cake (gingerbread in this case) was naturally or artificially sweetened and if it would be possible to judge the difference between sugar and sweeteners when not being mixed with anything else.

After deciding what to investigate, the students were divided in small groups which were encouraged to plan an investigation that could contribute to answering their questions. During the planning, the teachers initiated discussions about how investigations could be made robust and trustworthy (*trustworthiness*). Concepts like blind testing and fair test were discussed; would it, for example, make a difference if the soft drinks were cold or warm, would it matter if the test persons could see what they ate or drank, and would preconceptions matter to what the participants would answer (*trustworthiness*)? All groups came up with more or less differing solutions for how to go about their investigation (*creativity*). The teacher made sure that the requested products were available for the investigation. The students made all other practical arrangements and then performed their investigations with their peers as test subjects. One group decided that both the test subjects and the leader of the investigation should be blindfolded before tasting (or handing out) the soft drinks as a way to ensure that taste would not be biased by preconceptions. Another person in the group documented the results. When all groups had documented their results, they presented their conclusions to the rest of the class. The investigation and presentation were followed by a discussion about benefits of different ways to go about the investigation; could different approaches be mixed or could their methods be adjusted in order to receive an even better/more robust result? This could, at least implicitly, provide an idea of the benefits of collaboration and communication between (research) groups to get better results (*communication/argumentation/collaboration*). An explicit discussion of similarities and differences between students' investigations and researchers' investigations is important. Such explicit connections to the research society were made by discussing how, and why, different researchers or research groups can come up with different methods – that creativity is needed while planning and performing an investigation (*creativity*)[4].

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[4] It is also possible to use this part of the teaching sequence as an opportunity to discuss *creativity* in relation to researchers' interpretations and conclusions.

The teachers and students also discussed economic aspects and fraud, for example, if such an investigation could have been adjusted to fit the needs of the ones who had requested the research (*economic aspects*).

38.3 Conclusions

In this chapter, we have shared an example of how human elements of science were taught to 12-year-old students through the use of a thematic project. This specific teaching sequence has dealt with sugar and sweeteners, but other themes are possible such as usage of energy drinks, sunscreens, cell phones, plastic bottles, etc. Such issues could all be relevant for students in middle school. The actual theme should preferably be chosen from what is a current topic in media or among the students themselves at the moment.

The teaching sequence included readings reporting on scientific research, students' argumentation and debate, as well as students' engagement in authentic investigations. Thus, it is an example of highly contextualized NOS teaching. Worries have been raised in the literature about whether human elements of science are too complex for young students. The example, however, shows that teaching human elements of science to 12-year-old students in a meaningful way, indeed, is possible. Furthermore, the example shows that a highly *contextualized* teaching approach could be a fruitful approach to combine NOS learning goals with other curricular goals such as learning about science concepts or developing investigative abilities.

The involved teachers had not previously taught about the human elements of science explicitly but took the opportunity to do so when they got this chance to collaborate with colleagues and a researcher during a research project. Of course, the teaching led to unexpected experiences (positive and negative) for the teachers. This included, for example, that the teachers afterward expressed surprise concerning the students' reading difficulties (which made the reading time-consuming) and their lack of abilities for argumentation. In other cases, they were pleasantly surprised and impressed by their students' abilities to, for example, involve in discussions about abstract NOS issues. The teachers also put forward that students, who on other occasions were "silent," took on a very active role in the discussions (see also Leden et al. 2017).

Furthermore, the teachers stated that the teaching sequence served as a means not "only" to address NOS elements, but also provided opportunities for students to develop general skills that concerned: learning to discern messages in texts and to sort pros and cons, argumentation and discussion along with critical thinking. In addition, it provided opportunities to develop overarching science skills such as planning, performing, and evaluating investigations. The teachers also claimed that the teaching sequence as a whole will "develop students' abilities to be reflective, which makes me want to work like this more often." Thus, the example described in this chapter could also serve as an example of how NOS could constitute a path to teaching overarching general science as well as cross curricular skills. We have previously found that such arguments are important if teachers shall be willing to make the effort of including NOS in their classrooms (Leden et al. 2017).

Concerning the teaching of the NOS issues as such, we have seen that most of the key human elements were addressed during more than one part of the teaching sequence and also both implicitly (e.g., when students were engaged in performing their own investigations, or when reading the texts) and explicitly in teacher-led whole-class discussions. When students encounter the NOS issues embedded in different activities, the teachers gain starting points for addressing the same issues explicitly, and perhaps more generally. In this way, possibilities for NOS to become a natural part of science teaching are created.

References

Abd-El-Khalick, F., Bell, R. L., & Lederman, N. G. (1998). The nature of science and instructional practice: Making the unnatural natural. *Science Education, 82*(4), 417–436.

Aikenhead, G. S. (2006). *Science education for everyday life: Evidence-based practice*. New York: Teachers College Press.

Akerson, V. L., Buck, G. A., Donnelly, L. A., Nargund-Joshi, V., & Weiland, I. S. (2011). The importance of teaching and learning nature of science in the early childhood years. *Journal of Science Education and Technology, 20*(5), 537–549.

Allchin, D. (2014). From science studies to scientific literacy: A view from the classroom. *Science & Education, 23*(9), 1911–1932.

Bartholomew, H., Osborne, J., & Ratcliffe, M. (2004). Teaching students "ideas-about-science": Five dimensions of effective practice. *Science Education, 88*(5), 655–682.

Bell, R. L., Mulvey, B. K., & Maeng, J. L. (2016). Outcomes of nature of science instruction along a context continuum: Preservice secondary science teachers' conceptions and instructional intentions. *International Journal of Science Education, 38*(3), 493–520.

Brickhouse, N. W., & Bodner, G. M. (1992). The beginning science teacher: Classroom narratives of convictions and constraints. *Journal of Research in Science Teaching, 29*(5), 471–485.

Clough, M. P. (2006). Learners' responses to the demands of conceptual change: Considerations for effective nature of science instruction. *Science & Education, 15*(5), 463–494.

Clough, M. P. (2011). The story behind the science: Bringing science and scientists to life in post-secondary science education. *Science & Education, 20*(7–8), 701–717.

Farland-Smith, D., & McComas, W. (2009). Teaching the human dimension of science. *Science and Children, 46*(9), 48.

Hansson, L., & Leden, L. (2016). Working with the nature of science in physics class: turning 'ordinary' classroom situations into nature of science learning situations. *Physics Education, 51*(5), 55001–55006.

Herman, B. C., Clough, M. P., & Olson, J. K. (2013). Teachers' nature of science implementation practices 2–5 years after having completed an intensive science education program. *Science Education, 97*(2), 271–309.

Hodson, D. (2009). *Teaching and learning about science: Language, theories, methods, history, traditions and values*. Rotterdam: Sense Publishers.

Leden, L., Hansson, L., Redfors, A., & Ideland, M. (2015). Teachers' ways of talking about nature of science and its teaching. *Science & Education, 24*(9–10), 1141–1172.

Leden, L., Hansson, L., & Redfors, A. (2017). From black and white to shades of grey. *Science & Education, 26*(5), 483–511.

Lederman, N. G. (1995). Suchting on the nature of scientific thought: Are we anchoring curricula in quicksand? *Science & Education, 4*(4), 371–377.

McComas, W. F. (1998). The principal elements of the nature of science: Dispelling the myths. In W. F. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 53–70). Dordrecht: Kluwer Academic.

Nott, M., & Wellington, J. (1998). Eliciting, interpreting and developing teachers' understandings of the nature of science. *Science & Education, 7*(6), 579–594.

Chapter 39
Informal Learning Sites and Their Role in Communicating the Nature of Science

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Earlier chapters in this volume offer widespread agreement that aspects of the nature of science (NOS) or "features of science", the label preferred by Matthews (2012), ought to be an educational goal. The question that remains for this chapter, and many others, is how we might introduce learners to issues related to the nature of science in engaging and accurate ways. However, unlike other chapters where the learning about this topic is framed in school settings, ours addresses the role that informal science learning environments might play in contributing to understanding about the nature of science. However, we admit that while the informal learning domain is important, it is hard to define and difficult to study, but the potential it offers makes the study of non-school learning compelling. This is particularly true with this focus on learning about NOS which has its own instructional challenges even in the formal education domain. Our task, therefore, is to ask how informal science education can make a positive, even distinctive, contribution to learning about the nature of science.

In this chapter, we will first define and consider the nature and purpose of informal science education, particularly in relation to formal science education. We then discuss the potential found in several exemplars of informal science education – learning in museums, learning in the field and learning through biographies – to contribute to learning about the nature of science. These three exemplars are not, of course, intended to be exhaustive. There are many other important sites of informal science education (e.g. zoos, aquaria, botanical gardens, magazines, films, TV documentaries, the Internet more generally). We will conclude with some thoughts and

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6_39

cautions from our own experiences regarding NOS learning outside of schools. We begin this chapter with some definitions, perspectives and general principles and throughout consider the frustratingly sparse literature on NOS learning beyond the classroom.

39.1 What Is Informal Learning?

The definition of formal or in-school learning is likely one that is widely shared. Such learning usually features a classroom and/or a curriculum with stated learning goals and/or assessments to gauge progress and accuracy of learned information and an agenda that typically is not based on what learners wanted or needed to know. On the other hand, informal learning is essentially in every other place where people gain new experiences and information. Traditionally, museums, science centres, zoos, aquaria, botanical gardens and related institutions are labelled as informal learning sites, but this definition could easily be expanded to include libraries and all they contain, media, the Internet and virtually anything with which a person could interact and gain new understanding. This wider scope of possibilities is called free-choice learning by Falk (2001). Free-choice therefore is an umbrella term that includes the classic informal sites (museums, for instance) and perhaps should be the preferred term, but we will stick with informal learning here for simplicity and because that label dominates the literature.

We could complicate things more by stating that the world of out-of-school learning is therefore divided into "formal-informal sites" (those with explicit learning goals involved in programming, typically employing individuals charged with education matters) and "informal-informal sites" where learning is likely recognised but is not central to the mission. This distinction may be found by comparing a museum and its myriad exhibits, objects and labels with the local park where science is encountered in a much less curated fashion. Likewise, field trips for students may be open-ended, unstructured learning experiences or, at the other pole, tightly structured learning experiences that differ from formal laboratory exercises only in their location (cf. Allen 2004).

We accept two basic premises with respect to informal learning. One is the noteworthy statistic that "on average, only about 5 percent of an American's lifetime is spent in the classroom, and only a small fraction of that is dedicated to science instruction" (Falk and Dierking 2010, p. 488). The second is the abundance of research demonstrating that, in fact, people really do learn remarkable things (both valid and invalid) on their own out of school. As Falk and Dierking (2000) point out, engaging in informal learning may not produce experts but leave those who engage with such settings more motivated for future learning and likely more knowledgeable. They remind us "that people learn in museums is easy . . . [but] harder to prove" (Falk and Dierking 2000, p. 149). No educational setting can guarantee that participants will learn what experts know, but schools have tests to gauge learning and informal settings rarely do (Mujtaba et al. 2018).

Unfortunately, researchers have recently come to understand that some will deliberately seek out information sources that are designed to reinforce individuals' biases, but even without this factor, few routinely put themselves in situations to be challenged. "Given the free-choice nature of museum experiences, visitors very selectively pick and choose what they want to learn more about, and these decisions are very strongly influenced by what they already know and are interested in" (Falk and Storksdieck 2005, p. 119). Furthermore, according to Afonso and Gilbert (2007) and Medved and Oatley (2000), informal learning experiences even in museums are more likely to reinforce what visitors already know than to assist in the development of new – and more accurate – knowledge. This leads to the challenge that all learning sites need to be in the business of "changing minds", a task that becomes increasingly difficult once formal schooling is complete. This is particularly the case in an Internet and social media age where what more and more people watch, hear and read – for instance, about climate change or vaccinations – is algorithmically determined on the basis of their previous choices.

There is also the reality that many who choose to visit any of the range of non-school settings do so for entertainment, not education. This mindset on the part of visitors, even those who might accept an "edutainment" motivation for their visit, means that most such visitors probably do not expect to learn anything. Those who hold this view will pass their time in a pleasant environment rich with unrealised educational possibility. Frank Oppenheimer (1975), founder of the *Exploratorium* in San Francisco, once said that "no one ever flunks a museum …" (p. 11), and that may be true if the museum and visitor hold no educational goals for the visit. However, when curators, designers and museum educators plan a gallery or exhibit based on learning goals and visitors learn nothing or, worse, learn the wrong lessons, it seems that the museum has indeed failed.

39.2 Learning in Schools and in Non-school Settings

There has long been a belief that informal learning about science is a positive educational experience for young people; to a certain extent, this notion has been substantiated by research. Such learning is often cited as contributing positively to students' ideas about science as well as their enjoyment of it (Zoldosova and Prokop 2006; Amos and Reiss 2012). Traditionally, many school curricula have placed importance on out-of-classroom activities such as fieldwork and museum visits in subjects like geography, environmental science, history, art and science itself (Braund and Reiss 2006; Scharfenberg et al. 2008). Moreover, the authenticity afforded by such opportunities has more dramatically shaped some innovative approaches to science curricula in countries (e.g. Canada and Australia) with a tradition of promoting the importance of cultural relevance and "real-world" experience for meaningful learning (Roth et al. 2008).

There have been many influential accounts of the differences and relationship between formal and informal learning. Wellington (1990) pointed out that formal learning tends to be compulsory, structured, sequenced, assessed, certificated, more closed, teacher-led, teacher-centred, classroom- and institution-based, relatively asocial and “high currency” and results in relatively few unintended learning outcomes. Informal learning, on the other hand, was characterised by Wellington as being voluntary, haphazard, unstructured, un-sequenced, non-assessed, non-certificated, open-ended, learner-led, learner-centred and more social; such learning has many unintended outcomes (ones that are more difficult to measure) and is generally less valued by the formal assessment system. All in all, it seems clear that informal learning has immense potential to advance learning, but this potential is not straightforward for educators to realise (McComas 2006).

Stocklmayer et al. (2010) offer three models of the relationship between the informal and formal education sectors:

1. The two sectors are distinct. The informal sector uses science to provide entertainment, and it changes in line with market forces, while the formal sector is determined by governments (national curricula, inspection regimes, etc.).
2. There is some interaction between the informal and formal sectors; while the formal sector takes the lead in providing science education to students, it makes use of the informal sector to support student learning and/or engagement.
3. The two sectors work in close alignment; the informal sector is closely integrated into the everyday working of the formal sector, and therefore, a third space for science education results.

Our view about informal learning is that it occupies a space closer to the second and third of these models than the first but no such orientation is required. It is enough to recognise that we take informal learning about science to be any science learning experiences that sit outside conventional full-time education. Furthermore, we agree with Stocklmayer et al. (2010) that informal education can complement formal education.

Roth et al. (2008), who have explored the role of authentic experiences such as doing science in the field, have shown that from a young person’s perspective, there are multiple benefits to creating opportunities for local, real-life projects. More generally, there is growing evidence that, in addition to expecting that students learn about NOS and traditional science content, there are opportunities for socialisation and building self-confidence. Indeed, many studies have highlighted the personal, socio-cultural and physical benefits associated with informal learning (e.g. Falk and Dierking 2000).

39.3 Opportunities and Challenges: NOS Learning in Informal Environments

There are few studies that have examined NOS learning in the informal world, but several offer some encouraging results. Shouse et al. (2010) and Stocklmayer et al. (2010) suggest that visitors’ experiences with exhibits may improve NOS understanding, specifically with respect to an appreciation for how knowledge in science develops. In a study that looked at informal science educators, Holiday and Lederman (2013) found that subjects "demonstrated a strong understanding about NOS but views about the certainty of science were prevalent" (2013, p. 1). This result apparently stands in contrast to the typical finding that science teachers have insufficiently developed views of the NOS domain.

Considering another less studied informal learning opportunity – television – Dhingra (2003) states that:

> … we need to acknowledge the existence of the wide range of messages about science and scientists appropriated by students from television as well as from a range of other sources. Such messages about science and scientists interact with and influence classroom learning of science. We cannot ignore the powerful effects of … family, community, informal experiences with television, and the Internet, as well as interaction among these forces when we look at science education. (Dhingra 2003, p. 235)

Dhingra looked specifically at the kinds of messages about science and scientists that students may get from television, one of the more prevalent of the free-choice learning modalities. Given the range of ways in which science and scientists are portrayed on television, one can only imagine the range of confused and inaccurate understandings that viewers must develop. Consider just the image of scientists that one would develop while flipping channels from public television's generally accurate picture of science to programs like the X-Files and classic depictions from 1950s of radiation-induced monsters and the inevitable alien invasions.

Sandoval (2005) has summarised the literature on students' understanding of science and reports that many have trouble with four central issues: that science (1) is constructed by people, (2) varies in certainty, (3) has a diversity of methods and (4) has different forms of knowledge (hypothesis, theory and law, for instance). Of course, these are major elements of the nature of science that we agree should be communicated to learners. In a major report on learning in non-school or everyday environments, Bell et al. state "We recognize that the evidence for contributions from everyday science learning venues toward [these issues] suggests less contribution than for other strands" (2009, p. 116).

39.3.1 Teaching Aspects of NOS in Schools and Beyond

However, the most important concern for NOS instruction in and beyond school is found in the work of scholars (such as Abd-El-Khalick 2001, 2005; Abd-El-Khalick and Lederman 2000; Akerson et al. 2000; Khishfe and Abd-El-Khalick 2002; Bell et al. 2011; Abd-El-Khalick and Akerson 2009; Schwartz et al. 2004; Bell et al. 2016) who make it clear that NOS instruction must be explicit, provide opportunities for learners' reflection and, ideally, be contextualised, although this last element is not as well established as the others (Bell et al. 2011; Kishfe and Lederman 2006). Just as in schools, NOS learning must be deliberately mediated and facilitated. It is likely that Sandoval's (2005) conclusions are just as valid among those learning about NOS on their own as when experiencing in-school instruction.

We remain steadfast in our view that non-school environments can play a role in enhancing NOS understanding. Many informal sites do provide contexts for learning and offer the excitement that comes when learners can interact with objects and exhibits. However, the required elements of an explicit focus on NOS and opportunities to reflect on new understanding are usually absent. It may be profitable to consider the following example regarding the gulf between the potential for NOS learning and the reality that exists even in well-designed environments like museums.

In many natural history museums, such as the Humboldt in Berlin and the Darwin Centre in the Natural History Museum in London, visitors can look behind the scenes to see some of the immense collections that lie at the heart of these important facilities. These aggregations of vast numbers of animals and plants, pinned, labelled and lying quietly on shelves and in cabinets might "say" nothing to the casual observe and leave the impression that such institutions are more related to art museums than science sites.

A longer look might reveal, for instance, in an open drawer of hundreds of moths that there is a range of colours found among members of the same species. The simple but important conclusion is that this visitor has discovered a law or generalisation. This species of moth can be red, brown, or black but never white or yellow (at least as far as that collection reveals). Let us consider the potential for learning about "laws" – a key NOS element in the natural history museum. Even when a rare visitor takes the time to look carefully at these countless moths, (s)he will not have learned about laws because of the lack of an explicit and reflective opportunity to do so. There must be some mechanism (a sign, a docent, an interactive challenge) available to help the visitor in thinking about patterns, generalisations and laws in a valid fashion for this NOS element to be considered. Likewise, even if museum-goers can look behind the scenes and see scientists at work, what might they learn about how science is practised? Sure, they will see the accruements of science (lab coats, test tubes, machines and devices), but they will learn almost nothing about how scientists behave as a social group without guidance.

These examples are not necessarily indictments of museums, because perhaps educators there had no desire that visitors learn anything about NOS. However, one might argue that museums, field sites and similar informal environments have even more potential than do schools (which may lack the physical examples, experiences and the context) to teach important lessons about how science functions, what rules it obeys and what kinds of knowledge it produces. Perhaps it is best simply to state the obvious, namely, that informal learning sites are rich with unrealised potential regarding teaching about aspects of the nature of science.

39.4 Case Studies of NOS in Diverse Informal Environments: Possibilities for Practice

In this next section, we will consider how NOS might be a focus in three non-school areas including museums, field settings and using biography with an element that involves a visit to a historical property. We offer these as prospects and possibilities and to remind ourselves that there is much to be gained by considering what such informal science learning activities can do to help interested individuals experience and potentially learn about the nature of science. In focusing on these examples, our intention is not to dismiss other possibilities (e.g. learning through plays – see Shephard-Barr 2006) but simply to provide enough space and offer enough detail to begin articulating the possibilities that they afford for learning.

39.4.1 NOS Learning in Museums

At first sight, museums, even science museums, might seem a somewhat strange locus for learning about the nature of science. After all, museums surely entail, above all, a presentation of objects in relation one to another, as they have since their earliest days as *Wunderkabinette* in the houses of the wealthy. In that sense, what a visitor or an individual "visiting" on-line sees is a given arrangement of science as mediated by successive collectors, curators and administrators. The arrangement itself may support some learning goals while deterring others. However, there is a growing literature on the affordances for learning about science in museums both in general and specifically about the history and philosophy of science (Heering et al. 2013; Faria et al. 2015; Evans et al. 2016; Andre et al. 2017).

It may not be immediately clear, but even in museums, there are at least two ways to organise the objects found therein. There is the display where objects are available for viewing without any overt educational objective or story line, but someone put the objects down as they are and that can lead visitors to form certain conclusions. The opposite of this is the exhibit which may consist of a series of displays related to each other and designed to be encountered in a specific sequence. An example could be the contrast between a roadside menagerie with individual animals in enclosures and a modern zoo where animals found together in nature are in the same area of the zoo, typically with some explanatory text on a panel. The American Museum of Natural History has reorganised its complete collection of prehistoric animals in line with finding from contemporary cladistics. These models and skeletons are now arranged in a visually and scientifically compelling fashion with metal arrows embedded in the floor leading to small towers that discuss important branch points in evolution. Even though there is a film explaining the organising principle, it is admittedly very likely that only a small proportion of visitors learn all that the exhibit designers intended. Nevertheless, this is a clear attempt by a natural history learning to help visitors appreciate the way in which science has resulted in the production of new knowledge.

This notion of display/exhibit design is much the same as occurs in formal science education. A learner in school is presented with a curriculum, mediated by a teacher. Consider, for example, the teacher decisions related to sharing the equations of motion with students in a formal science class. The teacher must decide whether to introduce the topic of motion through mathematical equations, by including a historical account of Galileo, Newton and others, using hands-on or other practical work that might include an air track, computer simulations or whatever. Comparably, science museums must also decide how to introduce the science with which they want visitors to engage. This reality puts the onus on science museums to help visitors appreciate that the narrative they present is a constructed account that, in turn, directs visitors toward specific potential learning goals.

A good example of the nature of these decisions comes from the ways that museums communicate the topic of evolution. Tony Bennett (2004) has looked at nineteenth-century studies in geology, palaeontology, natural history, archaeology and anthropology and "trace[s] the development, across each of these disciplines, of an 'archaeological gaze' in which the relations between past and present are envisaged as so many sequential accumulations, carried over from one period to another so that each layer of development can be read to identify the pasts that have been deposited within it" (Bennett 2004, pp. 6–7). Bennett concludes that evolutionary museums "are just as much institutions of culture as art museums" (p. 187).

Monique Scott too has written about evolution in museums (Scott 2007). Scott's work, in contrast to that of Bennett (2004), has more to do with contemporaneous exhibits than with historical ones. Using questionnaires and interviews, she gathered the views of nearly 500 visitors at the Natural History and Horniman Museums in London, the National Museum of Kenya in Nairobi and the American Museum of Natural History in New York. Perhaps her key finding is that many of the visitors interpreted the human evolution exhibitions as providing a linear narrative of progress from African prehistory to a European present. As she puts it:

> Progress narratives persist as an interpretive strategy because they still function as a conceptual crutch … Many museum visitors, particularly Western museum visitors, rely upon cultural progress narratives – particularly the Victorian anthropological notion that human evolution has proceeded linearly from a primitive African prehistory to a civilized Europe – to facilitate their own comprehension and acceptance of African origins. Overwhelmingly, museum visitors relate to origins stories intimately, and in ways that satisfy or redeem the images they already have of themselves. (Scott 2007, p. 2)

To be blunt, this is a disastrous state of affairs, an illustrative example of how visitors can leave with a false impression when NOS is not adequately addressed in museums. So, what might one hope that science museums would do to facilitate better understanding about NOS when putting together exhibitions about evolution? Even if we presume that a museum decides to concentrate on the mainstream scientific account of a topic such as evolution, without the intelligent design debates, there are still many decisions (conscious or otherwise) that those putting together an exhibition make, all of which will affect what visitors take away about the features of science:

- How much does one oversimplify (the too-linear story of the evolution of the horse)? Too little simplification and the typical visitor is going to learn almost nothing, overwhelmed by difficult detail. Too much oversimplification and what our visitor learns may be no better than a reinforcement of error (cf. Scott's point above about a linear narrative of progress).
- To what extent should the curator(s) concentrate on scientific consensus, and to what extent should they address scientific controversy, for example, over the importance of punctuated equilibria and Lamarckism in evolution, and the relationship between micro- and macroevolution?
- To what extent should the social and cultural contexts of evolution be addressed (e.g. the reception by Victorian society and in France of Darwin's *On the Origin of Species* in 1859)?

Of course, comparable decisions are made frequently by teachers, but science museum exhibitions and other museum presentations of science cannot, unlike classroom teachers of science, rapidly alter their presentations to take account of the particular learners in front of them (Reiss 2012).

39.4.2 Museums and the Nature of Science: Unfortunate and Encouraging Examples

We would enthusiastically welcome more displays and exhibits focusing on specific elements of the nature of science. In mathematics, one standout example that, in part, addresses philosophical issues along with traditional content was *Mathematica: A World of Numbers … and Beyond* by the world-famous design team of Charles and Ray Eames. This exhibition was originally located at the California Museum of Science and Industry and now resides at the New York Hall of Science. However, there seems to be nothing comparable targeting communication of key elements of NOS.

39.5 *A Question of Truth*: NOS at the Ontario Science Centre

One of us (WFM) was briefly encouraged by the prospect of an exhibition with a potentially useful NOS focus that first opened in 1997 at the Ontario Science Centre in Toronto, Canada (and then toured to other institutions). This exhibition, *A Question of Truth: Race, Bias and Science*, involved the clear message that there is inherent bias in science. This, of course, is one of the human elements of science that members of the public should understand. The message that should be communicated is that the distinctive expectations and experiences of researchers – or bias – can help them sort through data and reach valid conclusions more effectively. At the same time, such individual bias can prevent scientists from seeing the value of certain facts, particularly if they are pointing to conclusions that are contrary to their expectations. The lesson about bias in science that should be taught is that bias exists but the scientific endeavour is grounded in argumentation, peer review and transparency with respect to data and elements that are designed to minimise bias, thus allowing the scientific enterprise to move closer to a valid description of nature.

Unfortunately, this exhibition portrays science in a very odd light with its focus differing from the goals of the nature of science on which most would agree. In a video designed to advertise the exhibition, the curator Hooley McLaughlin states, "western science is biased ... this exhibition explains that provocative fact". Later he adds, "There are many ways of knowing … but whose ways are taken to be the real science?" as if there are multiple kinds of "science" or that all ways of knowing should be thought of as equally useful.

In another film that all visitors were invited to see within the exhibition the narrator says, "Because science is so effective, some may have come to believe that western scientists and the culture they derive from are superior …". This is the real thrust of the exhibition – that some have used science to justify the unjustifiable such as slavery and discrimination. We certainly agree that using science in this fashion is unacceptable but can make little sense of the implication in the film that because there is some utility in an Earth-centred model of the solar system, it is somehow not wrong or even equally valid. Rather than use this Kuhnian example of scientific revolution and talk about the self-correcting aspect of NOS, the exhibition designers paint an overly critical and distinctively post-modernist view of science. The exhibition makes a valid point that science should not be used in inappropriate ways but misses a great opportunity to discuss the worth of science. Instead, it presents a misleading view of science that all but guarantees that visitors will be less secure in their understanding of NOS after viewing the exhibition. One might express some optimism by stating that if a major museum can mount an exhibition with an oddly focused NOS message, just imagine what they could do by designing a better portrayal of how science works.

39.6 Scientist for a Day: Thinking About NOS at the Science Centre Singapore

An example of a targeted and generally accurate museum exhibition that explicitly attempts to communicate aspects of the nature of science in a systematic way is "Scientist for a Day", currently found at the Science Centre Singapore. This permanent exhibit occupies a large space with an inviting display panel featuring illustrations of and quotes from Aristotle, Hume, Newton, Bacon and – most surprisingly – philosophers of science Karl Popper and Thomas Kuhn. This may be a first in any science museum to feature these two scholars who are well known in philosophy circles but certainly not to the public. Museum visitors are led into the hands-on part by a graphic on floor outlining the so-called scientific method with the five steps including “observe”, “hypothesise”, “experiment” and “conclude” with a feedback loop linked to the idea that should the hypothesis not be supported, a new one must be created. The text in the on-line introduction to the exhibition calls the scientific method “a flexible process” and does discuss “pursuing a curiosity … using pre-knowledge, ingenuity and creativity …”. However, what is delineated on the floor could be misleading since museum visitors will be unlikely to have reviewed the on-line materials or be challenged further in this limited portrayal of scientific methodology.

There are many stations in the exhibition that could best be described as experiences with scientific phenomenon more so than with the nature of science itself. These include the blending of red, green and blue lights into other colours; the actions of the classic drinking bird that bobs its head as water evaporates from its beak; the transfer of energy from one ball to another in a Newton’s pendulum; a cloud chamber; the role of the electron microscope in revealing the world of the very tiny; and other similar demonstrations with which visitors can engage. Other stations in the exhibition are more clearly focused on understanding “how science works” as evidenced by the associated text. There is a discussion of Occam’s razor, a comparison of the accounts of science by Kuhn and Popper, and materials on skepticism and pseudoscience, making predictions and the design of a valid experiment by accounting for all variables. There are also several do-it-yourself lab sessions facilitated by a museum explainer, including timing with a pendulum, Hooke’s law and an exploration of types of electrical circuits.

This exhibition is groundbreaking in that it exists at all, with a clear focus on explaining some underlying notions about how science functions. Unfortunately, many of the individual experiences provided contain notions that are poorly stated or so complex that visitors may not accurately learn some of the NOS lessons intended by the exhibit designer. For instance, the term “proof” is used in several places with no discussion of how this word should be used in a scientific context. Occam’s razor is included as if it is a valid description of scientific reasoning generally, but there are countless examples of where it does not hold true. The text in the panel regarding Popper’s views of falsification state that “scientists should always try to prove their ideas wrong, rather than continually prove them right”. The term “prove” here is problematic, and the complexity of Popper’s recommendation certainly cannot be easily understood with just the simple statement provided. Even the brief introductory quotes from scholars such as Popper and Kuhn are stated as if one could just read them and understand the distinctions between their views.

There are two effective exhibits that focus on the idea of precision in making scientific measurements, but the opportunity is missed when failing to discuss the role played by prior knowledge of scientists when making observations. The importance of model making in science is included in another exhibit, although the implication seems to be that such models always represent reality. Many models – peculiarly computer simulations – in science are designed to make accurate predictions of phenomena with little concern for their precise correspondence with reality.

In the final analysis, this is an impressive first step in the exposition of elements of NOS in an informal institution. There are very few science sites that would be so brave as to dedicate an entire space to empiricism, intuition, rationalism, falsification, modelling, skepticism, predictions and methods. It is incredibly forward thinking for the exhibit designers to recognise that instead of just demonstrating countless scientific phenomena – a typical agenda for such museums – it is equally important to help visitors understand how knowledge is created and validated in science. The Science Centre Singapore has announced that it will soon relocate and with this move will have the opportunity to re-envision their treatment of how aspects of NOS might best be communicated. An improved iteration of an exhibition such as "Scientist for a Day" could help to define what is possible in sharing NOS with the public in museums and other free-choice environments, and we certainly support their doing so.

39.7 Learning Science in the Field

If science museums offer a kind of staged science, perhaps learning in the field allows a more direct engagement with science. To a certain extent, this is indeed the case though; of course, a science educator taking learners on a field trip must make decisions about where to go, what to look at and what to do. These decisions connect to issues related to the nature of science.

In the sciences, fieldwork is sometimes likened to laboratory work, such that "the field" for ecologists is the equivalent of "the lab" for molecular biologists. As Hawley (2012) writes, "It is in the nature of laboratory and classroom experiments to separate objects from their environments … But in the 'natural' sciences it is only by putting objects and laws in particular contexts that we can see how they work in terms of empirical effects" (p. 88). Thus, as one of the workshop participants in Lambert and Reiss (2014) put it, fieldwork is one distinct component of learning science: "not all science happens in test tubes and young people need to realise this" (p. 8). Braund and Reiss (2006) have argued for the potential of learning outside the classroom to afford school science with greater authenticity.

If this authentic practice is properly mediated by a knowledgeable guide, students can experience many key NOS elements first hand. Considering the NOS elements that may be encountered as fieldwork brings conceptual, cognitive, procedural and social elements together (Lambert and Reiss 2014).

Conceptually, fieldwork encourages us to understand that most phenomena have a "history". This history – for example, the consequences of previous agricultural practices for present-day vegetation – can be discerned through careful observations undertaken in the field. Such fieldwork demands the application of thought processes that are more difficult to recreate in the classroom, for example, using data that may be incomplete and provisional, synthesising multiple forms of data and being tentative in drawing conclusions. Procedurally, it is important for students to witness and be part of interpretive and naturalistic science, where variables cannot be tightly controlled and where arguments need to be weighed.

Fieldwork can engage students in the iterative processes of drafting and redrafting data collection instruments (including the identification of good questions to investigate) as well as analysis and drawing conclusions; it can provide situations where students learn with and from each other as well as with and from their teachers and the environment.

More generally, the investigation of "real-world" settings offers students opportunities to understand the uniqueness of "place" and the notion of context – countering the "view from nowhere" that formal science education sometimes presents. Students can be motivated by working in unfamiliar settings (which can stimulate "awe and wonder", including an appreciation of beauty, e.g. when undertaking the live trapping of small mammals or observing the night sky) and experience the "unfamiliar" in the familiar/local context and stimulate curiosity (e.g. by devising one-meter field excursions using a piece of string of that length). Students can therefore learn through direct experience and/or observation of the world, thus linking theory and practice, and come to appreciate the importance of variability, data handling and statistical modelling. They can explore different "ways of seeing" and use all the senses to explore landscapes/phenomena and realise the need to be cautious in drawing conclusions, given the messiness of the real world (Kennedy 2006) that often does not behave as systems and models predict.

As a result, there is the potential for students to develop what we might term "real-world learning". Such learning can encourage such "habits of mind" as investigating, experimenting, reasoning and imagining and such "frames of mind" as curiosity, determination, resourcefulness and reflection.

Finally, there are typically social consequences to learning science in the field. The iterative processes of discussion and redrafting can require extended social interaction in meaning making and, perhaps paradoxically, lead to more "independent" learning. It can also enhance students' awareness of ethical questions, e.g. with regard to other living organisms, and have the additional benefit of deepening teachers' knowledge of students and their capacities.

39.8 Learning About NOS Holistically: Gaining a Sense of Process and Place

This last example of informal learning blends two elements – written narrative and a visit to a historical property. Each of these could function well in isolation, but together, they provide a more complete picture of the life and work of that individual than would be possible alone. The idea here is that by bringing these two data sources together, one can more readily appreciate how science is done – with the methodology shared by all scientists but also including knowledge of the idiosyncratic ways of work that define an individual investigator. One of the clearest examples of this blended type of informal learning is found with Charles Darwin in an example that concludes this section.

As has been pointed out elsewhere in this book, there are many reasons why reading a biography of a scientist can help in learning about the nature of science. A careful reading of an autobiographical account or biography can tell the reader much about what it is like to work as a scientist. There are many examples, but our favourites include the first-hand account of the discovery of the structure of DNA (Watson 1968) and biographies such as those by Box (1978), Browne (1995, 2002), Farmelo (2009), Isaacson (2008) and Keller (1984) which focus on the lives of Ronald Fisher, Charles Darwin, Paul Dirac, Albert Einstein and Barbara McClintock, respectively.

The book approach has many advantages as an informal learning tool. Of course, people can read in a field that is already of interest; it is surprising how many popular books and biographies exist to fill this void. However, the major NOS challenge shared with all informal learning opportunities is that the reader must have some idea of what to look for. One of us (WFM) teaches a semester-long class in aspects of the nature of science and, as a culminating activity, students read some account of scientific discovery or a biography autobiography of a scientist and then pick out elements of NOS reflected in that account. It would be very difficult to know what to look for in terms of "how science works" if one does not already have some idea of "how science works" in general.

39.8.1 Charles Darwin: An Example of Process and Place

Charles Darwin is known by many as the man who provided the foundation for all biology with his theory of evolution by natural selection and countless other discoveries about the natural world. His case provides an incredible opportunity for informal learning because many of his original writings, including *The Voyage of the Beagle* and *On the Origin of Species*, are so accessible. The first biology book one of us (MJR) ever read, at the age of 17, was the last that Darwin wrote – on earthworms (Darwin 1881). Even with only an introductory knowledge of NOS, this book would point out Darwin's careful and patient use of observations, his enthusiastic experimentation (e.g. on the hearing abilities of earthworms with one of his sons playing the bassoon to some) and his attempts to use mathematics to extrapolate how much earthworms build up soil.

Through Darwin's own hand (and with the occasional assistance of the several excellent biographies of Darwin himself such as Browne (1995, 2002) and Desmond and Moore (1992)), readers can appreciate what the nature of science looked like to Charles Darwin and how he undertook his scientific work. It is possible to visualise the role played by his upbringing and subsequent – his academic shortcomings at school and university, the role of happenstance in his formation as a scientist, the Beagle voyage, his views on religion and slavery, the wealth of information we have about his large family and his delight in them, the controversies that his work raised and his relationship with Alfred Russel Wallace (who also proposed natural selection) – and these mean that it is relatively easy to interest students in him. It is his ways of working, along with the theory of evolution by natural selection, that make him so suitable a resource for education, especially science education. In MJR's role as a Trustee of the Charles Darwin Trust, and with two of the Trust educators, Carolyn Boulter and Dawn Sanders, he edited *Darwin-Inspired Learning* (Boulter et al. 2015), further exemplifying this strategy and pointing out that many of Darwin's experiments can easily be reproduced in instructional settings.

Several scientists, though far too few, can be better understood by visits to their laboratory or house, but the example of Darwin is almost unique because his house has been extraordinarily well preserved and is open to the public. A visit to Down House, Charles Darwin's family home in the village of Downe, Kent, run by English Heritage, brings together the various strands of this chapter on learning NOS in informal environments. Down House is a museum with well-designed exhibits that bring to life the working methods of one of the world's great scientists while providing insights into his domestic life and its relationshiop to his scientific pursuits.

The insights about how Darwin worked can only be achieved by understanding how Darwin lived, and that is much more likely with a visit to Down House. Here visitors can examine Darwin's botanical experiments in the greenhouses or trace his footsteps along the famous "sandwalk" which provided him with exercise and the opportunity for uninterrupted thinking time. In addition, those coming in person with some preparation, can seek out the carnivorous and other plants that fascinated Darwin and understand the role of the "worm stone" that he used to measure the rate of soil formation. He strategically blended experimentation with his acute powers of observation and tremendous ability to synthesise vast amounts of information and produced general laws as a result. Of course, understanding the notion of laws (and their distinction from hypotheses and theories) is a vital *NOS* element that all should understand. How fitting it would be if Down House visitors might come to understand why saying "evolution is just a theory" makes no sense!

39.9 Concluding Thoughts

This book has as its central premise the idea that there are some shared notions about science that all students and citizens should understand. These include three clusters, the *Tools and Products of Science* (empiricism, scientific methods and the nature of laws and theories), *The Human Elements of Science* (with creativity, a degree of subjectivity and the interplay of science and society) and *The Limits and Extent of Science Knowledge* (the distinction between science, technology and engineering, the tentativeness but durability of science and the limits that constrain and direct the scientific enterprise).

We need knowledgeable teachers, engaging classrooms and good school laboratories, but anything that occurs in schools – particularly in laboratories – occurs in simplified environments, stripped-down, isolated opportunities to see but a version of the reality which exists in richer detail just beyond the school walls. Learners need to see science in context and explore real-world ethical issues when human influences must be considered to attain full understanding. Therefore, we have argued here that informal science learning can indeed help learners to appreciate important aspects of the nature or features of science and act as a sturdy bridge to link the relative brief world of school with lifelong learning. However, as we have seen, it is not an easy task for the informal environment or for the visitor/learner to gain NOS understanding. So, what can be done? To this question, we offer several responses.

There is widespread agreement on the aspects of the NOS that everyone should understand and belief that informal environments can play a role in that understanding. Ironically, however, the key to learning about the nature of science out of school may be learning about it in school. A prior, accurate understanding of aspects of NOS will guide and extend learning for those visiting non-school sites. Of course, we recognise that those in the informal learning community have very little control over the formal education curriculum. Furthermore, educators, whether in formal or informal environments, typically present accounts of the history and processes of science in ways that mislead students about how science derives its authority (Allchin 2003, 2012).

Another challenge is found in the kind of inquiry that often occurs at informal sites. Put simply, visitors are free to wander and attend to anything they like. Gregory and Miller (1998, p. 197) remind us when the Ashmolean museum in Oxford opened, its stated aim was "to further the knowledge of Nature acquired through the inspection of Particulars". For museum scientists, this is precisely what occurs, but how likely is it that museum visitors will discover in this fashion? Consider our example of someone wandering through a museum, rich with potential for teaching about laws or generalisations in science. Unless a visitor already had some idea about the nature of laws, from their uninformed and unguided perspective, this opportunity is very likely to be missed. So, informal learning sites with an agenda for communicating NOS must challenge and inform visitors. This could be done with a film, game, brochure, app or some other tool to share knowledge of NOS and then invite guests to learn more.

A museum of science and industry is a perfect site to convey understanding that science, technology and engineering are distinct domains, each with their own philosophical foundations. A zoo might point out that animals that live in similar environments or have similar life styles have shared traits. Doing so could point out the law (shared physical traits)-theory (why is there similarity?) distinction. A nature centre might pose the challenge that visitors try to identify as many living things as possible in a plot of ground and then follow up with a discussion about "what is living?" Following this, the task could be assigned again, helping learners to understand that science has a tentative component and conclusions change with additional information.

Of course, we would be delighted to see informal sites develop accurate and immersive exhibits, directly targeting the topic of "how science works". In fact, that would be a wonderful title for such an exhibition with well-considered NOS learning goals, engaging displays, helpful docents (often called "explainers") and knowledge of what visitors already know about the topic. As Heering (2017, p. 406) reminds us in a recent essay on teaching science in museums:

> ... bringing the museum staff together with learners on a variety of levels might be fruitful not just for the latter but also for the former, as they are enabled to develop a firsthand understanding of the knowledge and questions that people of various ages and various social backgrounds may bring to the science museum.

Visitors are typically willing to receive what zoos, museums, nature centres and other free-choice sites want to give them, whether that is entertainment, education or both. It is certainly time to leverage what we know about NOS, what we know about teaching NOS in an explicit and reflective fashion and what we know about the strengths of informal science learning environments.

References

Abd-El-Khalick, F. (2001). Embedding nature of science instruction in preservice elementary science courses: Abandoning scientism, but …. *Journal of Science Teacher Education, 12*(3), 215–233.

Abd-El-Khalick, F. (2005). Developing deeper understandings of nature of science: The impact of a philosophy of science course on preservice science teachers' views and instructional planning. *International Journal of Science Education, 27*(1), 15–42.

Abd-El-Khalick, F., & Akerson, V. (2009). The influence of metacognitive training on preservice elementary teachers' conceptions of nature of science. *International Journal of Science Education, 31*(16), 2161–2184.

Abd-El-Khalick, F., & Lederman, N. G. (2000). Improving science teachers' conceptions of the nature of science: A critical review of the literature. *International Journal of Science Education, 22*(7), 665–701.

Afonso, A. S., & Gilbert, J. K. (2007). Educational value of different types of exhibits in an interactive science and technology center. *Science Education, 91*, 967–987.

Akerson, V. L., Abd-El-Khalick, F., & Lederman, N. G. (2000). The influence of a reflective activity-based approach on elementary teachers' conceptions of the nature of science. *Journal of Research in Science Teaching, 37*, 295–317.

Allchin, D. (2003). Scientific myth-conceptions. *Science Education, 87*, 329–351.

Allchin, D. (2012). Science con-artists. *American Biology Teacher, 74*(9), 661–666.

Allen, S. (2004). Designs for learning: Studying science museum exhibits that do more than entertain. *Science Education, 88*(Suppl. 1), S17–S33.

Amos, R., & Reiss, M. J. (2012). The benefits of residential fieldwork for school science: Insights from a five-year initiative for inner-city students in the UK. *International Journal of Science Education, 34*, 485–511.

Andre, L., Durksen, T., & Volman, M. L. (2017). Museums as avenues of learning for children: A decade of research. *Learning Environments Research, 20*, 47–76.

Bell, P., Lewenstein, B., Shouse, A. W., & Feder, M. A. (Eds.). (2009). *Learning science in informal environments: People, places, and pursuits*. Washington, DC: The National Academies Press.

Bell, R. L., Matkins, J. J., & Gansneder, B. M. (2011). Impacts of contextual and explicit instruction on preservice elementary teachers' understandings of the nature of science. *Journal of Research in Science Teaching, 48*, 414–436.

Bell, R. L., Mulvey, B. K., & Maeng, J. L. (2016). Outcomes of nature of science instruction along a context continuum: Preservice secondary science teachers' conceptions and instructional intentions. *International Journal of Science Education, 38*(3), 493–520.

Bennett, T. (2004). *Pasts beyond memory: Evolution, museums, colonialism*. London: Routledge.

Boulter, C. J., Reiss, M. J., & Sanders, D. L. (Eds.). (2015). *Darwin-inspired learning*. Rotterdam: Sense.

Box, J. F. (1978). *R. A. Fisher: The life of a scientist*. New York: Wiley.

Braund, M., & Reiss, M. (2006). Towards a more authentic science curriculum: The contribution of out-of-school learning. *International Journal of Science Education, 28*, 1373–1388.

Browne, J. (1995). *Charles Darwin: Voyaging*. London: Jonathan Cape.

Browne, J. (2002). *Charles Darwin: The power of place*. London: Jonathan Cape.

Darwin, C. (1881). *The formation of vegetable mould through the action of worms*. London: John Murray.

Desmond, A., & Moore, J. R. (1992). *Darwin. Harmondsworth*. Penguin.

Dhingra, K. (2003). Thinking about television science: How student understand the nature of science from different program genres. *Journal of Research in Science Teaching, 40*(2), 234–256.

Evans, E. M., Weiss, M., Lane, J., & Palmquist, S. (2016). The spiral model: Integrating research and exhibit development to foster conceptual change. In D. M. Sobel & J. Jipson (Eds.), *Cognitive development in museum settings: Relating research and practice* (pp. 36–64). New York: Psychology Press.

Falk, J. (2001). *Free-choice science education: How we learn science outside of school*. New York: Teachers College Press.

Falk, J., & Dierking, L. (2000). *Learning from museums*. Walnut Creek: Alta Mira Press, Rowman and Littlefield.

Falk, J., & Dierking, L. (2010). The 95 percent solution. *American Scientist, 98*, 486–493.

Falk, J., & Storksdieck, M. (2005). Learning science from museums. Historia, Ciencias, Saude – Maguinhos. *Rio de Janeiro, 12*(Suplemento), 117–143.

Faria, C., Guilherme, E., Gaspar, R., & Boaventura, D. (2015). History of science and science museums. *Science & Education, 24*(7–8), 983–1000.

Farmelo, G. (2009). *The strangest man: The hidden life of Paul Dirac, quantum genius*. London: Faber and Faber.

Gregory, J., & Miller, S. (1998). *Science in public: Communication, culture and credibility*. Cambridge, MA: Perseus.

Hawley, D. (2012). The 'real deal' of earth science: Why, where and how to include fieldwork in teaching. *School Science Review, 94*(347), 87–100.

Heering, P. (2017). Science museums and science education. *Isis, 108*(2), 399–406.

Heering, P., Klassen, S., & Metz, D. (Eds.). (2013). *Enabling scientific understanding through historical instruments and experiments in formal and non-formal learning environments*. Flensburg: Flensburg University Press.

Holiday, G., & Lederman, N. (2013). Informal science educators' views about nature of scientific knowledge. *International Journal of Science Education, Part B*. https://doi.org/10.1080/21548455.2013.788802.

Isaacson, W. (2008). *Einstein: His Life and Universe*. New York: Simon and Shuster.

Keller, E. F. (1984). *A feeling for the organism: The life and work of Barbara McClintock*. San Francisco: W. H. Freeman and Company.

Kennedy, B. A. (2006). *Inventing the earth: Ideas on landscape development since 1740*. Oxford: Blackwell.

Khishfe, R., & Abd-El-Khalick, F. (2002). The influence of explicit reflective versus implicit inquiry-oriented instruction on sixth graders' views of nature of science. *Journal of Research in Science Teaching, 39*(7), 551–578.

Khishfe, R., & Lederman, N. G. (2006). Teaching NOS within a controversial topic: Integrated versus nonintegrated. *Journal of Research in Science Teaching, 43*, 395–418.

Lambert, D., & Reiss, M. J. (2014). *The place of fieldwork in geography and science qualifications*. London: Institute of Education, University of London. Available at http://www.field-studies-council.org/media/1252064/lambert-reiss-2014-fieldwork-report.pdf

Matthews, M. (2012). Changing the focus: From nature of science to features of science. In M. S. Khine (Ed.), *Advances in nature of science research* (pp. 3–26). Dordrecht: Springer.

McComas, W. F. (2006). Science teaching beyond the classroom: The role and nature of informal learning environments. *The Science Teacher, 27*(7), 24–29.

Medved, M. I., & Oatley, K. (2000). Memories and scientific literacy: Remembering exhibits from a science centre. *International Journal of Science Education, 22*(10), 1117–1132.

Mujtaba, T., Lawrence, M., Oliver, M., & Reiss, M. J. (2018). Learning and engagement through Natural History Museums. *Studies in Science Education*. https://doi.org/10.1080/03057267.2018.1442820.

Oppenheimer, F. (1975). The Exploratorium and other ways of teaching physics. *Physics Today, 28*(9), 9, 11, and 13.

Reiss, M. J. (2012). Learning out of the classroom. In J. Oversby (Ed.), *ASE guide to research in science education* (pp. 91–97). Hatfield: Association for Science Education.

Roth, W.-M., van Eijck, M., Reis, G., & Hsu, P-L. (2008). Authentic science revisited: In praise of diversity, heterogeneity, hybridity. Rotterdam: Sense.

Sandoval, W. A. (2005). Understanding students' practical epistemologies and their influence on learning through inquiry. *Science Education, 89*(4), 634–656.

Scharfenberg, F.-J., Bogner, F., & Klutke, S. (2008). A category-based video-analysis of students' activities in an out-of-school hands-on gene technology lesson. *International Journal of Science Education, 30*, 451–467.

Schwartz, R. S., Lederman, N. G., & Crawford, B. A. (2004). Developing views of NOS in an authentic context: An explicit approach to bridging the gap between NOS and scientific inquiry. *Science Teacher Education, 88*, 610–645.

Scott, M. (2007). *Rethinking evolution in the museum: Envisioning African origins*. London: Routledge.

Shephard-Barr, K. (2006). *Science on Stage: From doctor Faustus to Copenhagen*. Princeton: Princeton University Press.

Shouse, A., Lewenstein, B. V., Feder, M., & Bell, P. (2010). Crafting museum experiences in light of research on learning: Implications of the National Research Council's report on informal science education. *Curator: The Museum Journal, 53*(2), 137–154.

Stocklmayer, S., Rennie, L., & Gilbert, J. (2010). The roles of the formal and informal sectors in the provision of effective science education. *Studies in Science Education, 46*, 1–44.

Watson, J. (1968). *The double Helix: A personal account of the discovery of the structure of DNA*. New York: Atheneum.

Wellington, J. (1990). Formal and informal learning in science: The role of interactive science centres. *Physics Education, 25*, 247–252.

Zoldosova, K., & Prokop, P. (2006). Education in the field influences children's ideas and interest toward science. *Journal of Science Education and Technology, 15*, 304–313.

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W. F. McComas (ed.), *Nature of Science in Science Instruction*,
Science: Philosophy, History and Education,
https://doi.org/10.1007/978-3-030-57239-6

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Alexander Gerber is a PhD student in Science Education at Indiana University Bloomington. During his first few years of his program, he has taught two elementary field experience courses and one elementary science methods course, in which the approach to teaching NOS described in this chapter was employed with elementary preservice teachers. Prior to beginning his graduate studies, he taught science to young children in a number of informal science settings. In this position, he continually promoted ways for children to think not only about science ideas but also how scientists came to understand these ideas (i.e., the practices and nature of science).

Lena Hansson is an Associate Professor of Science Education at Kristianstad University, Sweden. She has a background as an upper secondary teacher. She earned a PhD in Science Education with dissertation research focused on world view issues in relation to science learning. She has broad interests in science education, but her main research focus lies at the intersection between nature of science perspectives and cultural perspectives on science teaching. One such interest regards how different images of science, communicated in science class, includes and excludes different groups of students. She has published in journals such as *Science Education*, *Science & Education*, *Research in Science Education*, and *International Journal of Science Education*. She serves as a board member in the International History, Philosophy, and Science Teaching Group Council. Lena is also engaged in research-based developmental projects and pre- and in-service teacher training, aiming at bridging the gap between science education research and school practice.

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Onur Imren completed his undergraduate degree in Science Teaching at Dokuz Eylul University, Turkey, in 2009 and his master's degree in Science and Education at the University of Bristol, United Kingdom, in 2011. He is currently a doctoral student at the National Centre for STEM Education, University of Limerick, Ireland. His doctoral research investigates the use of commercial video games for learning scientific practices in secondary schools.

Fred Janssen is Professor of Science Education at ICLON Leiden University Graduate School of Teaching. Three overarching questions guide his research program: (1) How to identify and represent domain-specific ways of thinking for teaching? (2) How to teach domain-specific ways of thinking? (3) How to learn to teach domain-specific ways of thinking? Currently, 4 postdocs and 14 PhD projects are connected to this research program. We build local theories for teaching a particular domain-specific way of thinking and develop a general theory that can inform and guide the development of local theories, both conceptually and methodologically. This emerging general theory draws on research on bounded and ecological rationality in multiple disciplines.

Kostas Kampourakis is a researcher at the University of Geneva, where he teaches courses at the University's Teacher Training Institute and Section of Biology. He has just completed a term as the Editor in Chief of the journal *Science & Education*. He is Book Series Editor for *Science: Philosophy, History and Education* (Springer), is Coeditor of the books *Teaching Biology in Schools: Global Research, Issues, and Trends* (Routledge, 2018) and *Newton's Apple and Other Myths About Science* (Harvard University Press, 2015), as well as Editor of *The Philosophy of Biology: A Companion for Educators* (Springer, 2013); he is also the Author of *Turning Points: How Critical Events Have Driven Human Evolution, Life, and Development* (Prometheus Books, 2018), *Making Sense of Genes* (Cambridge University Press, 2017), and *Understanding Evolution* (Cambridge University Press, 2014). His main research interests include teaching, learning and public understanding of nature of science, evolution, and genetics.

Nausica Kapsala is a biologist and a storyteller. She holds a master's degree in Modern Trends in the Teaching of Biology with the Aid of New Technologies and is a PhD candidate in the Faculty of Education, NKUA. She has also graduated from the School of Storytelling organized by the Center for the Study of Dissemination of Myths and Folktales. She attended the educational program My Traditional Heritage, Our Stories (MYTHOS) on multilingual storytelling and artistic interpretation. Her research interests lie in finding effective methods of teaching biological concepts and the dissemination of science. She has participated as a researcher in a variety of European programs, has published 18 articles in edited volumes and conference proceedings both in Greek and English, and has worked as a biology teacher in Lyceums and voluntarily at the Social Tutorial of the Municipality of Zografou, Greece, and part-time as a storyteller. She is a founding member of the social cooperative The House of Oral Tradition, Mythologion.

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Mojtaba Khajeloo is a PhD candidate in Science Education at the University of Missouri, Columbia. He completed her MSc in Biochemistry from the University of Tehran and her BSc in Microbiology from Karaj Azad University, Iran. His general research interests hover around design, development, and evaluation of science instruction at college levels. His current research involves investigating college students' understanding of complexity in biological systems.

Ilse Landa graduated at the University of Wageningen as a molecular scientist. After completing a PhD in the field of molecular biology, she shifted her focus to chemistry education. Today, she works as an A-level chemistry teacher and writes for an educational publisher. Recently, she started a postdoctoral research at the Free University of Amsterdam, aiming at the improvement of conceptual chemical reasoning of A-level students within the scope of scientific perspectivism.

Lotta Leden is a senior lecturer in Science Education at Kristianstad University, Sweden. She has a background as a secondary teacher in mathematics and science and technology and as a special education teacher. Her research focuses on NOS teaching at different stages in the educational system (preschool to teacher education). Her PhD project emphasized teachers' perspectives on the teaching of NOS in compulsory school (ages 6–16). She has a broad interest in inclusive education and science education and is involved in pre- and in-service teacher education.

Judith Sweeney Lederman, PhD, is an Associate Professor and Director of Teacher Education in the Department of Mathematics and Science Education at Illinois Institute of Technology, Chicago, IL. She has been the Curator of Education at the Museum of Natural History and Planetarium in Providence, RI, and has taught middle- and secondary-level physics and biology and bilingual elementary science. She has over 600 national and international presentations/publications on the teaching and learning of Scientific Inquiry and Nature of Science in both formal and informal settings. She is Coeditor for the *Journal of Science Teacher Education*, an Author for a National Geographic elementary science book series, and Coauthor of an elementary science teaching methods text. She was a Fulbright Fellow working in South Africa with teachers at the Cradle of Humankind and is on the Board of Directors of the National Association for Research in Science Teaching (NARST).

She has also served on the Board of Directors of the National Science Teachers Association (NSTA) and is Past President of the Council for Elementary Science International (CESI).

Norman G. Lederman, Distinguished Professor of Mathematics and Science Education at Illinois Institute of Technology, was an award-winning biology/chemistry teacher. Internationally known for his scholarship on students and teachers' conceptions of nature of science and scientific inquiry, he has authored or edited 10 books/chapters and over 200 peer-reviewed articles and has made more than 500 national and international conference presentations. He was Coeditor of both volumes of the *Handbook of Research on Science Education* and *School Science and Mathematics* and is currently Coeditor of the *Journal of Science Teacher Education*. He is Former President of the National Association for Research in Science Teaching and the Association for the Education of Teachers in Science and served as Director of Teacher Education for the National Science Teachers Association. He is a Fellow of the American Association for the Advancement of Science and the American Educational Research Association. He received the Distinguished Contributions to Science Education Through Research Award from the National Association for Research in Science Teaching and the Distinguished Service to Science Education from the National Science Teachers Association.

Cathleen Loving, PhD, is a former high school biology teacher and now Associate Professor Emerita in the Department of Teaching, Learning and Culture at Texas A&M University. She served at the university for 23 years, the last 5 as Director of Graduate Studies, and retired in 2014. Her primary contributions are both teaching and publishing in the area of pedagogical improvements in the way the nature of science is presented in classrooms. Few science teachers have had the opportunity to conduct scientific investigations and therefore may find it difficult to fully appreciate the roles of failure, conjecture, theory-building, and the role of theory as a guide for much of science. Therefore, one major emphasis in her work was to develop strategies to help distinguish science from pseudoscience, a major problem in the news today.

Jennifer Maeng is currently a Research Assistant Professor at the University of Virginia's Curry School of Education. She completed her PhD in Science Education from the University of Virginia. She is a former high school chemistry teacher and has expertise both in K–12 science professional development and in program evaluation. Currently, she is the PI of the Virginia Initiative for Science Teaching and Achievement Elementary Literacy Integrated with Science (VISTA ELIS) project, which provides professional development to support elementary and middle school teachers in integrating nature of science, literacy, technology, and engineering into science instruction through problem-based learning. She has published both research-based and practitioner articles in STEM education.

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Evangelia Mavrikaki holds a PhD in Biology. She is an Associate Professor and a member of the Laboratory of Science Teaching and Epistemology and Educational Technology of the Faculty of Primary Education of the National and Kapodistrian University of Athens, Greece. Among her research interests are biology teaching, health, and environmental education. She has authored or coauthored many articles or chapters in Greek and international journals or books and is the author-coauthor of 15 books including the Greek Gymnasium biology textbooks. Her work has received 177 Greek and International citations. She has been project leader or senior researcher in many projects and has served for four years as an elected member of the executive board – in charge for Educational Issues – of the Pan-Hellenic Association of BioScientists.

William F. McComas is the inaugural holder of the Parks Family Endowed Professorship in Science Education at the University of Arkansas following his experiences as a secondary biology and physical science teacher in suburban Philadelphia and Professor at the University of Southern California. He is interested in the intersection of philosophy of science and science instruction, enhancement of laboratory teaching, informal science learning, evolution of education, and science for gifted learners. He has given more than 100 keynote speeches in the United States and internationally and writes frequently on a variety of science education topics. He is the Editor of this volume and the book *The Language of Science Education: An Expanded Glossary of Key Terms and Concepts in Science Teaching and Learning* (Sense/Brill, 2014) and Coauthor of a pictorial account of The Scopes Monkey Trial (Acadia, 2016). He currently serves as the Editor of *The American Biology Teacher*. He has been honored for his work in evolution education, research in biology teaching, innovations in college science teaching, and mentorship. He was a Fulbright Fellow at the Centre for the Advancement of Science and Mathematics Teaching and Learning, Dublin City University in Ireland, and of the American Association for the Advancement of Science (AAAS) and was recently named a Distinguished Professor.

Hanno Michel is a science education researcher at the Leibniz Institute for Science and Mathematics Education in Kiel, Germany. In his PhD project, he theoretically and empirically investigated the relation between NOS understanding and conceptual understanding in science, in particular regarding the energy concept. Currently, he is involved in projects that aim at enabling students to actively engage in socioscientific discussions and decision-making processes regarding Germany's transition toward renewable energy.

Jacqueline Muijlwijk-Koezen is a Professor of Innovation in Human Health and Life Sciences at VU University Amsterdam. Her group aims to apply the theory of science education within the context of human health and life sciences. Her research focuses on innovations and didactics in science and education, with special emphasis in pharmaceutical sciences and drug discovery research as embedded within the Amsterdam Institute for Molecules, Medicines and Systems (AIMMS). Her research on new teaching concepts and innovative learning approaches lead to new insights and are implemented several times in various study programs of the Faculty of Sciences. The group has two research lines: (1) active learning, especially inquiry-based learning, and (2) the nature of science (NOS) and its reflection in science education which led to the new field of scientific perspectivism in education.

Bridget K. Mulvey is an Associate Professor of Science Education at Kent State University in Kent, Ohio, USA. She completed her master's degree in Geology from Indiana University at Bloomington and her PhD in Education with a science education emphasis from the University of Virginia. She taught undergraduate and K–12 science for more than 10 years. Her research focuses on nature of science, inquiry/science practices, and technology.

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Nikos Papadouris works in the Center for Educational Research and Evaluation of the Cyprus Ministry of Education and Culture. He is a Research Associate with Learning in Science Group at the University of Cyprus, where he completed his PhD in Science Education. His research interests concentrate on student understanding of energy-related concepts as well as on the design of curriculum materials for promoting epistemic awareness.

Meredith A. Park Rogers is an Associate Professor of Science Education at Indiana University Bloomington. Her research involves investigating how various aspects of elementary teacher's professional knowledge base for teaching science (i.e., PCK) develop with experience, how the various knowledge components required for teaching science are influenced by contextual factors, and how interdisciplinary connections between STEM content areas can support elementary teachers in developing their broader professional knowledge for teaching science and mathematics. A core aspect of understanding teachers' knowledge for teaching science is how they think about and incorporate the nature of science (NOS) when teaching children about science. Therefore, he is also continually developing methods for supporting elementary teachers' understanding and implementation of NOS in their teaching of science.

Jennifer C. Parrish is an Assistant Professor of Science Education at the University of Northern Colorado. Prior to obtaining her PhD in Science Education from Middle Tennessee State University, she spent over a decade teaching middle school science and engaging students in authentic inquiry experiences. She currently teaches science content courses for preservice elementary teachers. Her research focuses on the development of teachers' conceptions of nature of science and scientific inquiry, with a particular interest in developing strategies to promote teacher reflection for professional growth.

Peter Heering has, since 2009, been a professor of physics and its didactics at the Europa-Universität Flensburg. He completed a PhD on historical and educational aspects of Coulomb's law in electrostatics at the Carl von Ossietzky Universität

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Erin E. Peters-Burton, Ph.D. is the Donna R. and David E. Sterling Endowed Professor of Science Education at George Mason University in Fairfax, Virginia. Her research agenda is focused on helping all students build self-awareness of how they learn science and engineering. She works to help students, particularly students who are underrepresented in STEM, see themselves as “science-minded” and helps teachers create classrooms that support student skills to develop scientific knowledge. To accomplish this, she pursues research projects that investigate ways that students and teachers can use self-regulated learning theory in science and engineering practices and employ critical components of inclusive STEM schools that can help all students succeed. She is the Director of the Center for Social Equity through Science Education C(SE)2, a group of researchers, educators, and university students who are dedicated to helping all people to have a richer understanding of science.

Gerald Rau teaches academic writing in the Department of Electrical Engineering at the National Chung Cheng University in Chiayi, Taiwan. After earning his PhD in Plant Breeding at Cornell University, he taught every middle and high school science course at least once during his 13 years as science coordinator at the American School in Taichung. He was also the Owner and Chief Editor of an academic editing company. He is currently completing a textbook and articles documenting the differences between science and engineering academic writing formats. His interest in the philosophy of science is reflected in his book, *Mapping the Origins Debate: Six Models of the Beginning of Everything*, which attributes disparate interpretations of the same evidence to different presuppositions and in presentations at NSTA, philosophy of science, and evolutionary linguistics conferences.

Rebecca Reiff-Cox is an Associate Professor at Hollins University in Roanoke, Virginia, where she supervises student teachers, teaches elementary science and secondary methods courses, and actively participates in local science fairs. She completed her PhD in Curriculum and Instruction with a major in Science Education from Indiana University in Bloomington, Indiana. She is a former biology, chemistry, and middle school science teacher with a passion to share scientific stories, adventures, and multiple pathways behind scientific discoveries (in other words, the wild side of science). She also has seen tremendous success introducing girls to physics in the 6th grade classroom through projects such as constructing marshmallow catapults and roller coasters!

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Ranu Roy recently graduated with her PhD in Science Education from the Indiana University Bloomington. During her doctoral studies, she has held the position of graduate associate instructor for the elementary science methods course. Each time she taught this course, she has considered ways to improve her discussions about NOS, which greatly contributed to the strategies described in this chapter. Prior to coming to the United States for graduate studies (both master's and PhD), he was a school teacher in Kolkata, India, for 10 years.

Susan Schwinning As a native of Germany, Susanne Schwinning earned her first degree at the University of Göttingen, majoring in Botany. Following that, she obtained her MS in Plant Physiology from the University of California, Davis, and her PhD in Ecology and Evolutionary Biology from the University of Arizona, Tucson. She became a faculty member in the Department of Biology at Texas State University in 2005 and was promoted to Professor in 2016. She has taught undergraduate courses in General Ecology and Plant Ecology and graduate courses in Ecological Modeling and Plant Water Relations. To date, she mentored 23 graduate students and 29 undergraduate students in conducting or participating in research. She serves as Associate Editor for three international research publications and has published 53 peer-reviewed research articles and book chapters on the topics of ecohydrology and plant ecology.

Cindi Smith-Walters is a Professor of Biology at Middle Tennessee State University and directs the MTSU Center for Environmental Education and Environmental Studies. For nearly 40 years, she has worked with individuals of all ages to share the wonder and joy of science. A founding board member of the Tennessee Naturalist Program, Tennessee Academy of Science Fellow, and award-winning educator, author, and presenter, she is interested in the teaching and learning of science in both formal and informal settings.

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Britt van der Ploeg holds a master in Biology and teaches Biology at the Bonhoeffer College in Castricum in the Netherlands. In her PhD project, she investigates how *scientific perspectivism* can function as a framework for a didactical approach to secondary science education. Her aim is to enable teachers to design lessons in which students develop scientific reasoning in mono- and multidisciplinary real-life contexts. Her project specifically focuses on the development of practical design heuristics for creating lessons in which scientific reasoning is promoted by way of guided multi-perspective reasoning. Additionally, tools are developed in this project for the assessment of student domain-specific reasoning skills.

Sandra Sturdivant West, PhD, is an Associate Professor of Biology at Texas State University and AAAS Fellow. She completed her BS in General Science and her MS in Marine Biology from the University of Houston and her PhD in Science Education from Texas A&M University. She is a former middle/high school science and Montessori teacher. She teaches science courses for elementary teachers and science methods, supervises science and math student teachers, and mentors in-service teachers. She is Chair of the Safety Advisory Board for the National Science Teachers Association and Coauthor of the *NSTA Guide to Planning School Science Facilities*. Her safety research has influenced science class size policies across the United States. Her Mix It Up: Correlated Science and Math Teacher Quality projects teamed grades 5–9 science and math teacher teams and their principals to provide professional development for integrating science and mathematics. She is a strong advocate for state science education policy based on research-identified best practices and has received state and national awards for her leadership.

Hanna Westbroek is Assistant Professor at the VU University Amsterdam. Her research is part of the bounded rationality research program and specifically focuses on the development and empirical testing of chemical and biological perspectives as a base for practical design tools. Additionally, she supervises a project that aims to connect perspectivist hypothesizing to designing experiments and two postdoc projects and two PhD projects within this program. Another part of her research specifically focuses on developing methods for using of a teacher's goal system of his/her teaching practice for understanding and developing teaching practice.

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