# Reading for Evidence and Interpreting Visualizations in Mathematics and Science Education

Stephen P. Norris (Ed.)

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CRYSTAL - ALBERTA
CENTRE FOR RESEARCH IN YOUTH, SCIENCE TEACHING & LEARNING
CRSNG NSERC
CREAS CRYSTAL

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Stephen P. Norris
December, 2011

# I. INTRODUCTION

FRANK JENKINS AND STEPHEN P. NORRIS

# 1. CRYSTAL—ALBERTA

## *A Case of Science-Science Education Research Collaboration*

### INTRODUCTION

In 2004, Canada's national funding body for scientific research, the Natural Sciences and Engineering Research Council of Canada (NSERC), for the first time asserted itself in kindergarten to grade 12 science and mathematics education. The Council issued a request for proposals to establish, on a pilot basis, Centres for Research in Youth, Science Teaching and Learning (CRYSTALs). The primary purpose of these centres was to "increase our understanding of the skills and resources needed to improve the quality of science and mathematics education (K-12)" (NSERC, 2005). Proposals were required to show how the centres would establish effective collaborations between scientists and mathematicians and science and mathematics educators. Five centres were funded across the nation.

This volume reports some of the outcomes of CRYSTAL—Alberta, the centre designated by NSERC to be the national leader. This chapter will set into historical context the significance of NSERC's initiative, describe how CRYSTAL—Alberta organized its research and dissemination agendas, and provide an overview of the subsequent chapters.

### HISTORICAL CONTEXT

The purpose and nature of school science and mathematics education have been topics of discussion for over 100 years in industrialized countries such as Canada. The United States has one of the longest histories of discussion of these topics and brings the topics back to the table very frequently. As early as 1894, a report by The Committee of Ten, prepared under the auspices of the National Educational Association, proposed that "the study of simple natural phenomena" (p. 117) begin in elementary schools with at least one period per day devoted to it, and that at least 200 hours be devoted to the study of physics and chemistry in high school. The basic rationale provided by the Committee was that the study of nature and of the scientific method were properly part of ordinary schooling and should proceed with the inclusion of time for experiments and laboratory work. Mathematics was similarly supported and a focus in instruction on promoting "clear and rigorous reasoning" (p. 25) was emphasized. During the middle of the twentieth century, James Conant (1951) was a United States' leader in upholding the role of science in democratic citizenship. The gist of his argument was that "matters of public policy

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are profoundly influenced by highly technical scientific considerations" (p. 19) so that some understanding of science is needed by "lawyers, writers, teachers, politicians, public servants, and businessmen" (p. 17). The U.S. continued to worry deeply about the condition of its science and mathematics education for the remainder of the 20th century and into the 21st. The National Science Foundation supported an entire program of science and mathematics curriculum development in the wake of the launch of Sputnik. The American Association for the Advancement of Science (2001, 2007) published a two-volume *Atlas of scientific literacy* as part of its Project 2061, a long-term initiative aimed at the reformation of science and mathematics education. The atlas provides some 100 maps that show how ideas in science and mathematics and about science and mathematics are related. Despite all of these efforts, the Committee on Science Learning, Kindergarten through Eighth Grade of the National Research Council (Duschl, Schweingruber, & Shouse, 2007) announced in the first sentence of the first page of its report of 2007: "At no time in history has improving science education been more important than it is today." In the same year, The National Academies were asked how to make improvements to the science and technology enterprise in the United States. The first recommendation of the Academics' Committee on Prospering in the Global Economy of the 21st Century was to "Increase America's talent pool by vastly improving K-12 science and mathematics education" (2007, p. 5).

A similar concern with the quality of science education has existed in Europe. For example, the United Kingdom experienced a push for reforming science education in the 1960s and 1970s through sponsorship by the Nuffield Foundation. A report funded by the Nuffield Foundation appearing in 1998 (Millar & Osborne, 1998) with the purpose of providing "a new vision of an education in science" (p. 1) has had considerable influence worldwide in reshaping the discussions about science education reform. Its over 500 citations are evidence of its impact. At around the same time, a Select Committee on Science and Technology (2000) of the U.K. House of Lords was announcing a "crisis of confidence" (p. 5) in science and that "[s]ociety's relationship with science is in a critical phase" (p.5). One year later, the government of the U.K. commissioned a study into the supply of high quality scientists and engineers, which found a "disconnect between the strengthening demand for graduates (particularly in highly numerate subjects) on the one hand, and the declining numbers of mathematics, engineering and physical science graduates on the other" (Roberts, 2002, p. 2).

In 2008, Osborne and Dillon made a report to the Nuffield Foundation on science education in Europe. In the report, they argued that current science curricula "are increasingly failing to engage young people with the further study of science" and do "not meet the needs of the majority of students who require a broad overview of the major ideas that science offers, how it produces reliable knowledge and the limits to certainty" (p. 7). A strong indicator of the failure of science teaching in the classrooms of industrialized nations, including those of Europe, is that there is a *negative* correlation of 0.92 between students' attitudes towards science and the United Nations index of human development (Sjøberg & Schreiner, 2005), a fact that was uncovered by the Research on Science Education (ROSE) study sponsored by Norway.

Canada's initiatives into science and mathematics reform prior to the NSERC initiative were modest by comparison to those of the U.S. and U.K. The Science Council of Canada was a government advisory board that existed for about 25 years starting in the late 1960s. In 1984, the Council produced a report from a four-year study on the state of science education in Canada (Science Council of Canada, 1984). In the Canadian federation, provinces have sole jurisdiction over education. Without the cooperation of the provinces on the collection of student achievement information, which the Council did not have, the most crucial data needed to report on the state of science education was not available. This lack of cooperation reduced the impact that the report had on science education in the country, even though several discussion papers that it commissioned have become classic readings on science education programs nationwide.

In 1997 work by the Council of Ministers of Education (CMEC), which is a body comprising the ministers of education and their staffs from the ten provinces and three territories, produced a framework of learning objectives for K-12 science for use across the country. The framework was for curriculum developers and was based upon a vision for scientific literacy aimed at developing "inquiry, problem-solving, and decision-making abilities, to become lifelong learners, and to maintain a sense of wonder about the world" (CMEC, 1997, p. 4). It was assumed that scientific literacy is fostered best "through the study and analysis of the interrelationships among science, technology, society, and the environment" (1997, p. iii). This framework remains in use more than a decade since its publication, and is one of the reasons that science curricula remain reasonably comparable from province to province to territory (for example, in their emphasis on science, technology, society, and the environment), even though each political entity maintains complete control over education in its jurisdiction.

NSERC entered this situation with its program of Centres for Research in Youth, Science Teaching and Learning. Being an organization that deals with science and engineering research funding, NSERC seemed not to understand the incredibly long time that it takes to make change in education. Moreover, it was not apparent that consideration had been given to the jurisdictional boundaries existing in the country, because the assumption seemed to have been made that there would be an uptake of research results in all jurisdictions. Also, although NSERC mandated as a condition of funding that science and mathematics educators and scientists and mathematicians collaborate on educational research and development, there was little history of such collaboration in the country and seriously competing views between the educators and scientists about the very nature of educational goals and educational research. Although it is assumed in science that many years and even decades can pass between the publication of a scientific finding and the translation of that finding into some useful product or practice, it was expected that any findings from the CRYSTAL research could be put to immediate use, which is contrary to the historical fact that educational research findings show a similar lag in application. The criteria used to evaluate the program did not take account of the fact that science and mathematics education research conducted in Canada is only a very small fraction of such research worldwide. Thus, it is reasonable to expect policy makers at ministries of education and school districts to look to the worldwide body of research, including that from Canada, in making the most informed decisions about educational practices. The result, in all likelihood because Canadian research output is such a tiny fraction of worldwide output, would be that Canadian research would not play a major role, unless it were aimed specifically to solve a parochial problem.

## CRYSTAL—ALBERTA RESEARCH AND DISSEMINATION MODEL

The research and dissemination model for CRYSTAL—Alberta involved many components. The research goal was to promote mathematics and science reasoning. To organize the research, a two-by-two matrix was employed: reasoning in mathematics and science and reasoning as displayed in text and visualizations. The same matrix was used both to classify the research projects and to organize the outreach resources on the outreach website. The collaborative research teams purposely included teachers, graduate students, education researchers and scientists. Undergraduate students also were included on some teams.

Dissemination of research from the program included components organized directly by the administration team of CRYSTAL—Alberta and components organized by individual researchers. In the latter case, researchers conveyed their research findings through presentations at teacher workshops and conferences and at research conferences. They also published their research in teacher association newsletters and journals and in peer-reviewed education research journals.

CRYSTAL—Alberta also organized formal dissemination of research through three national and two local conferences. The national conferences for the five CRYSTALs across Canada involved short presentations and discussions of research being conducted at each of the centres—a collaborative sharing of diverse research. Each centre had its own research and outreach goals, with only minor collaboration among researchers across centres. Local conferences sponsored by each centre involved teachers, consultants, outreach partners, ministry of education personnel, and graduate students, in addition to the education researchers and scientists. The local conferences allowed participants to select several short discussions of research during half-day or day-long agendas. The local conferences served to open lines of communication among partners in science education and to move the research results closer to implementation in classrooms.

As an example of a professional conference involvement, the annual Alberta Teachers' Association Science Council conference was a major annual event in local outreach and research dissemination. Each year CRYSTAL—Alberta shared a display and dissemination table with the Centre for Mathematics, Science and Technology Education (CMASTE). Researchers conducted presentations for classroom teachers and the CRYSTAL—Alberta Outreach Coordinator gave updates on the progress of outreach website resources. In addition the Outreach Coordinator gave multiple presentations to pre-service elementary and secondary teachers in mathematics and science education classrooms.

As another example of outreach activities that were sponsored by all centres, both the CRYSTAL—Alberta Speaker Series and the CMASTE Discussion Group were useful tools in disseminating research results to the local mathematics and science education communities. Visiting scholars and local graduate students were typical presenters, and research papers focused on mathematics and science reasoning were frequently discussed. One of the main advantages of this approach was to involve partners in science education (such as the Telus World of Science, a science centre and museum; and Inside Education, a non-profit environmental education organization), science consultants from surrounding school districts, and Alberta Education personnel with curriculum development and student assessment roles.

Internationally, CRYSTAL—Alberta has become known for its work on mathematics and science reasoning—both through dissemination at international education and science conferences and through international outreach projects. For example, resource materials are employed extensively in CMASTE-produced and UNESCO-sponsored Iraqi science teacher education lessons. The teacher education lessons are meant to transform and modernize Iraqi science education. The focus on scientific reasoning also resonates with the CMASTE and Inter Americas Network of Academics of Science (IANAS) partnership and its focus on inquiry-based science education. In this and other ways CMASTE has served as a continuing partner of CRYSTAL—Alberta.

The outreach component of CRYSTAL—Alberta mostly involved outreach to K-12 classrooms. An outreach website that communicated work on mathematics and science reasoning was created and called 'CRYSTAL—Alberta Outreach' (go to www.crystalalberta.ca, and follow the link). Links from the outreach website direct users to the visualization-based website (www.KCVS.ca). As described previously, the research was classified as either mathematics or science and text or visualization in a two by two matrix, and the outreach website sections were classified in the same way. This consistency between the research and the communication through outreach was a helpful element for the organization of the project.

Initially, a graduate student with classroom experience was employed to review the education literature on mathematics reasoning (Metz, 2008). She also searched for requirements about mathematics reasoning in the curriculum framework developed under the Western and Northern Canadian Protocol (WNCP) for mathematics K-9 (WNCP, 2006) and 10–12 (WNCP, 2008), and in National Council of Teachers of Mathematics (2000, 2006) curriculum documents. The interest in the forms of reasoning invoked in mathematics and in mathematics education is indicated in the abstract for the review:

> Mathematics has traditionally been defined in terms of deductive logic …. [This view] has been challenged by quasi-empiricist and fallibilistic views of mathematics…. (Metz, 2008)

The quasi-empiricist and fallibilist views of mathematics move mathematics reasoning beyond the normal deductive view to the possibility of hypothetico-deductive reasoning (allowing for falsifiability as in science) and inductive reasoning. The review of the literature and curriculum documents led to identification of forms of reasoning in mathematics and to the presentation of examples and exercises. The review was mined for outreach resources by an experienced classroom teacher. The resources, including textual introductions to the topic and exercises in text understanding, were posted on the outreach website under *Mathematics Reasoning Text*.

Another section of the outreach website attends to scientific attitudes, habits of mind, and dispositions to act and think in certain ways. Some science educators believe that scientific attitudes are that which remains of science learning after all else is forgotten. Some of the scientific attitudes discussed on the outreach website are: open-mindedness, critical-mindedness, respect for evidence, willingness to suspend judgment, willingness to change ideas, honesty, and tendency to question. This section is accompanied by a downloadable text file and an exercise, which can be found on the outreach website under *Science Reasoning Text* and *Scientific Attitudes*.

Reasoning can also be communicated through the nature of science (NOS) language used orally in the classroom and written in the resources, including assessment tools. It is impossible not to communicate a view of the nature of science through the language used in the classroom. The outreach materials created for the website include examples of the authority and degree of certainty in a knowledge claim. Examples of expressing authority include: "According to the evidence gathered in Lab 9.4. . ." and "Based upon Newton's second law. . .". Examples of the degree of certainty include: "Favourable judgements of the design, materials, procedures and skills indicate high confidence in the evidence and, therefore. . . "; and "The accuracy of the prediction as a percent difference is. . .". After professional development sessions, many participants indicated that the language element is one suggestion that they are able immediately to implement in their classrooms. These elements can be found on the outreach website under *Science Reasoning Text* and *Scientific Language.*

Scientific reasoning and NOS language use can also be understood and promoted through the use of primary literature, adapted primary literature, or hybrid adapted primary literature. The study of adapted and hybrid adapted primary literature produced fruitful collaborative research during the CRYSTAL—Alberta project. Educators and education researchers adapted primary research literature of collaborating scientists for use in elementary and secondary science classrooms. Research often centered on the students' understanding of the arguments provided by the scientists to gain acceptance of their knowledge claims. For example, scientists often anticipate alternative hypotheses, experimental designs, and procedures that might be suggested by other scientists. They openly write about these alternatives and provide their reasoning for making their selections. When the pedagogic purpose is to identify the scientific reasoning, the adaptation is slanted in that direction—as opposed to adapting the primary literature to promote understanding of the substantive science knowledge. Students can be asked to identify the scientific purpose of the investigation, the nature of science language used, and the line of argumentation. The potential of adapted primary literature is just starting to be tapped. One example involved helping summer research students in the Women in Scholarship, Engineering, Science & Technology Summer Research Program and in the Heritage Youth Researcher Summer Program to fruitfully read primary literature. These students worked in research laboratories for six weeks in the summer and were required to read primary research. Examples can be found on the outreach website under *Science Reasoning Text* and *Adapted Primary Literature*. A text-plus-visualization based example can also be found on the KCVS website under *Visualizations and Mathematical Modeling.*

The application of scientific reasoning for citizenship is another outreach component of the CRYSTAL—Alberta website. What kind of knowledge, processes, skills, and habits of mind do citizens need to evaluate claims to knowledge? Carl Sagan (1997) wrote that "… the tools of skepticism are generally unavailable to the citizens of our society. They're hardly ever mentioned in the schools, even in the presentation of science…" (p. 77). Some of the concepts presented for evaluating claims to knowledge on the outreach website are: (1) anecdotal evidence, (2) correlational study, (3) cause and effect study, (4) clinical trial, (5) duration of study, (6) sample size, (7) random sample, (8) placebo, (9) placebo effect, (10) double blind, (11) funding agency, (12) peer-reviewed, (13) respected journal, (14) bias, and (15) certainty. These concepts are needed for citizens to critically evaluate health, environmental, and other claims to knowledge. Exercises that apply these concepts are provided on the outreach website for classroom use under *Science Reasoning Text* and *Evaluating Claims to Knowledge*.

The KCVS website materials are not generally focused on the explicit description of mathematics and science reasoning. The focus rather is on deep understanding through the use of visualizations. Some of the visualizations created with partial support from CRYSTAL—Alberta include 9 global climate change applets, 18 modern physics applets, 9 special relativity applets, 7 chemistry applets, 1 mathematical modeling applet, and 7 elementary science applets. Some of the modern physics applets are accompanied by teacher and student resources created with CRYSTAL—Alberta support that explicitly attend to mathematics and science reasoning of the type described above: for example, the Photoelectric Effect and Rutherford Model applets. Some of the applets also direct teachers and students to classical primary literature for the interactive visualizations available. These applets can be found on KCVS website, and can be used directly from the site or they can be downloaded and used independently in the classroom.

Adapted primary literature can also be applied to education research. Typically, teachers do not read the primary literature of education research. CRYSTAL—Alberta undertook to publish much of its research through two issues of the Alberta Teachers' Association Science Council journal—the *Alberta Science Education Journal* (Alberta Teachers' Association, 2009, 2011). Research previously and subsequently published in education research journals was adapted for a teacher audience.

Sagan (1997) suggests, "The method of science, as stodgy and grumpy as it may seem, is far more important than the findings of science" (p. 22). A significant part of the method of science involves mathematics and science reasoning. If we have managed in some small way to advance this cause, we have succeeded. To become mainstream in the classroom, mathematics and science reasoning must be supported by classroom resources, instructional strategies, assessment tools, and curriculum outcomes. Significant work has been done and significant work remains to be done to complete the implementation of the research conducted by CRYSTAL—Alberta.

## OUTLINE OF THE BOOK

The book is divided into three sections: the first contains this introductory chapter; the second deals with reading for evidence; and the third, covers the work done on visualizations in science and mathematics.

Chapter 2, "Reading for evidence", is by Susan Barker and Heidi Julien, who bring a complementary set of skills to this topic. Susan's primary research interests are ecological education and biological education and their relationship with science education, particularly through practical work. Heidi focuses on information behaviour, information literacy, and information policy with a primary interest in promoting people's access to information in any context of their lives. Finding and evaluating information is an integral part of both scientific research and science pedagogies. In this chapter findings are presented from two CRYSTAL—Alberta research projects that examined how high school biology students find and evaluate information and how they make judgments to differentiate between scientific evidence and value statements. The contexts explored by the students were the Canadian seal hunt, climate change, and biomes. Science lends itself very well to discussions about the construction of knowledge and about accuracy of information that students may find on the internet or in textbooks. For example, the tentative nature of scientific knowledge arises frequently in such situations. The term 'information literacy' refers to the set of skills required to identify information sources, access information, evaluate it, and use it effectively, efficiently, and ethically. The evidence indicated that students generally possess unsophisticated information and scientific literacy skills yet they believe they are more competent. The authors propose a teaching model based on scientific inquiry that can assist students in being more effective in finding, handling, and evaluating information, as well as furthering their understanding of scientific inquiry. The work builds on Windschitl (2008), who views information-seeking tasks as supporting activities of inquiry that help prepare students to participate more meaningfully in the core activities of inquiry by acquainting them with necessary concepts, ideas, and skills. Barker and Julien argue that more attention to making connections between information literacy, scientific literacy, and science inquiry could promote a better understanding of the nature of science and of scientific reasoning.

Marie-Claire Shanahan's Chapter 3, "Reading for evidence through hybrid adapted primary literature", examines text pieces that integrate both narrative writing and adapted scientific writing as a way to support students in learning to read scientific text, specifically reading to identify the uses of evidence. The trend in science education has been to advocate hands-on opportunities for students and move away from teaching practices that rely heavily on textbook reading. Yore, Craig, and Maguire (1998) argue, however, that this emphasis has stifled efforts to use text in a valuable way in the science classroom. Fang et al. (2008) argue that current strategies deny students the opportunity to engage with and learn the specialized language of science and to see concrete examples of scientific reasoning. These researchers contend that to truly engage students in inquiry, the answer lies not in removing scientific text but in supporting students to learn with and from it. This chapter addresses this gap by exploring Grade 5 and 6 students' ability to recognize, evaluate, and reason with evidence presented in hybrid adapted primary literature. Students' oral discussions and writing are examined for the appropriate identification of evidence, the connections between this evidence and findings, and the degree of certainty ascribed to findings based on the nature of the evidence. Analyses suggest that the inclusion of narrative writing that explicitly addresses the decisions that scientists make with regards to evidence supports students in better identifying evidence later in the scientific report and demonstrating more complex reasoning with that evidence.

Chapter 4 by Jerine Pegg and Simon Karuku examines the ways in which science curricular resources provide students with opportunities to develop evidence-based explanations and the complex reasoning skills required in the coordination of evidence and explanation. Pegg and Karuku present the results of a content analysis of Alberta junior high school science textbooks and associated laboratory materials to determine the nature and extent of opportunities for students to engage in reasoning about scientific explanations. The content analysis was based on a framework that identified opportunities for students to engage in explanatory reasoning, and classified the nature of such opportunities at three levels: (1) the type of explanatory process (constructing, evaluating, or applying claims), (2) the type of explanation (e.g., causal or descriptive), and (3) the supports for the explanation that the text prompts students to include (e.g., evidence or reasoning). Findings of the analysis suggest that although the curricular resources provide multiple opportunities for students to engage in the construction of claims, they rarely require students to evaluate or apply claims. The resources also include limited explicit prompts for students to support claims with evidence or reasoning. Implications for using existing curriculum resources to engage students in the construction of explanations and argumentation are discussed.

"Reading the environment as text" is Chapter 5 by Susan Barker and Carole Newton. Comprehension of natural environments is value laden and culturally dependent and thus scientists and educators will construct different understandings of the same habitat. Scientists, for example, often provide us with evidence to understand the complexity of natural systems and educators interpret this evidence to make it relevant to the classroom or informal setting. Literacy is a form of understanding and so the processes by which we make sense of the environment can be seen as text or discourse rather than the environment itself. Stables (1996) argues that the environment is at least in part a social construct and that textual studies offer a valid means of studying it. In this chapter Barker and Newton explore how scientists and educators read the environment as text, as part of a collaborative venture in producing a site-specific science education resource. Stables (1996) indicates that traditional scientific approaches can further contribute to an understanding of the environment as text. The context for this chapter is Big Lake at Lois Hole Provincial Park, a Natural Area near Edmonton that has long been used for scientific research, teaching and recreation. Through this case study we explore the notion of reading the environment as text and demonstrate how both scientists and educators views are important when developing site-specific education resources for teaching science.

Chapter 6, “Visualizations and visualization in mathematics education”, is by John S. Macnab, Linda M. Phillips, and Stephen P. Norris. The role and effectiveness of visualizations in mathematics is both contentious and ambiguous. The contention arises from the belief by many mathematicians that visualizations tie universal mathematical concepts and thoughts inappropriately to specific objects, misleading students about the significance of the mathematical results. The ambiguity arises because the best mathematicians often are not the best visualizers. In mathematics education, the bulk of the research is aimed at visualization as a computational aid that often leads to the creation of new mathematics. One could use a visualization object to assist students to understand a mathematical object, which could lead to the creation of another object that is mathematically interesting in its own right. For example, a graph might be used to help a student to understand a function. The graph itself, however, is a new mathematical object with its own properties. It is then possible to take an interest in graphs that is independent of the original aim of the graph’s introduction. This chapter reports on select findings from a review of 30 empirical studies of visualization in mathematics education and addresses the following four questions: (1) How is visualization defined and conceptualized? (2) What theoretical perspectives inform the application of visualization in mathematics? (3) What is the research evidence on visualization in mathematics education? and (4) What are some recommendations for the most effective development and use of visualizations in mathematics?

Chapter 7, by John Braga, Linda M. Phillips, and Stephen P. Norris, is complementary to Chapter 6: “Visualizations and visualization in science education”. There has been a general consensus amongst science education researchers during the past 20 years that visualization objects assist in explaining, developing, and learning concepts in the field of science. However, the usefulness of visualization in science seems to have much to do with a match between the activity and the desired outcome. Visualization often involves using schematic or symbolic diagrams as computational aids. In these cases, the visual objects tend to be simple and direct. For conceptual understanding, richer objects in combination with verbal or textual instruction offer the possibility of rich experiences for students. The verbal component seems essential, because visualizations rarely can stand alone. This is especially true in science education, where difficult-to-imagine objects can be depicted dynamically for students to appreciate how these objects change over time. Finally, there appear to be important concepts that cannot be visually clarified leading to great disputes over whether visualizations have any place at all. This chapter reports on select findings from a review of 65 empirical studies of visualization in science education, addressing the following four questions: (1) How is visualization defined and conceptualized? (2) What theoretical perspectives inform the application of visualization in science? (3) What is the research evidence on visualization in science education? and (4) What are some recommendations for the most effective development and use of visualizations in science?

In Chapter 8, “Curriculum development to promote visualization and mathematical reasoning: Radicals”, Elaine Simmt, Shannon Sookochoff, Janelle McFeetors, and Ralph Mason describe a project with six high school mathematics teachers who designed curriculum resources for teaching specific content of high school mathematics through inquiry. Through this field-based project teachers wrote, implemented, and evaluated inquiry lessons that promoted visualization and reasoning. In preparing for sharing their materials with others, they recognised that curriculum resources offer spaces for imagining inquiry lessons in a high school mathematics class, not blueprints for building an inquiry classroom. They describe the ways in which a teacher incorporated manipulative materials into her lessons to engage the students’ mathematical reasoning and visualization skills. The chapter is illustrated with a series of lessons on radicals, a topic often treated in high school purely symbolically. In the lessons developed by the teacher a concrete geometric visualization of the radical is offered to learners. The case demonstrates how the use of materials in the high school mathematics classroom affords possibilities for meaning making by using the visible to trigger mathematical reasoning.

Brenda J. Gustafson and Peter G. Mahaffy authored Chapters 9 and 10, “Introducing grade five students to the nature of models”, and “Using computer visualizations to introduce grade five students to the particle nature of matter”. The chapters are related and focus on the development and appraisal of six computer visualizations designed to help Grade 5 children (ages 11–12) begin to learn about the particle model of matter, physical change, and chemical change. Chapter 9 begins with an introduction to research literature used to inform the content and design of the visualizations. This background provides the rationale for designing visualizations about small, unseen particles that include ideas about a) the nature of models (all models are ‘good enough’ models that have strengths and limitations), and b) the difficulty of believing in an unseen world. Chapter 10 provides a description of six computer visualizations, and discusses a subset of data gathered from two Grade 5 classrooms that piloted the visualizations. These data provide insight into some children’s thinking as they considered concepts related to small, unseen particles and the nature of models. The discussion and conclusion focus on the relationship between children’s views about the nature of models and their views about matter and how teachers can use this information to inform their teaching.

## SUMMARY

Together the chapters attend to the challenges of promoting mathematics and science reasoning and deep understanding. The historical context provided a backgrounder to the need for research on mathematics and science reasoning. The research and dissemination model described some of the CRYSTAL—Alberta attempts to distribute past and present research and outreach resources locally, nationally, and internationally. Also provided were examples of resources, instructional strategies, assessment items, and potential curriculum outcomes that can be used to promote mathematics and science reasoning. The range of the conceptualization in the research indicates the breadth of what might initially be seen as a narrow topic and, again, indicates the difficulty in producing applied education research on any particular topic. Experience in education programs most often shows that at least 10 years are required to move from research through development into implementation. Perseverance with and belief in the goals will decide the eventual outcomes of CRYSTAL—Alberta.

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# II. READING FOR EVIDENCE

SUSAN BARKER AND HEIDI JULIEN

# 2. READING FOR EVIDENCE

## INTRODUCTION

When we went to school our reading of information was quite different from that of students today. Information we had access to was limited in range and predominantly in print form and there was an implied perception of trust in the information due to the accountability that was attached to print forms. Today we live in a 'digital universe' where information is rapidly expanding; it is instantly and continually accessible without having to leave the confines of our classroom or home, and almost immediately available from the time of generation and often with little evidence of source or validity. The information varies from vitally important matters of life and death to the trivial and unimportant, such as what a distant relative ate for supper. The International Data Corporation (IDC) predicts that digital information will grow 47% in 2011 alone to reach 1.8ZB ($1.8 \times 10^{21}$ bytes) and rocketing to 7 ZB by 2015 (IDC, 2010). This enormity of information changes the landscape of how in our everyday lives we filter, select, and read information and how it is shared and used in classrooms. Of particular importance is how students themselves find and evaluate information—tasks that teachers have set for students for generations but now occurring in a rapidly changing digital universe.

Within the field of science, the terms 'information' and 'evidence' carry a meaning that goes beyond the general use of the terms, and thus in science teaching it is more appropriate to use the prefix 'scientific'. Scientific information and evidence are integral parts of the nature of science itself with scientists relying on scientific information generated through the work of other scientists to lay the ground for new research questions, to substantiate methodology and verify results, and to keep up with new developments and new sources of research data. Indeed scientists spend around two to three months a year retrieving and reading scientific literature, in particular journal articles (King, Tenopir, & Clarke, 2006). However not any old piece of information will do; articles in Wikipedia for example are unlikely to be used to substantiate methodologies by a scientist planning new avenues in stem cell research due to its open source nature and unidentified authorship. The culture of science expects members to use peer-reviewed published work whether it be electronic or print scientific journals. The peer-review process provides a quality control that verifies research methodologies, results and conclusions, and the use of findings as evidence, which policy makers can then utilize to make decisions and form policies. Moreover, the digital universe has precipitated new ways for scientists to share and publish their research, in this case making their research even more accessible to laypeople (Bjork, 2007) with information often being frontier science where consensus has not yet been reached

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(Kolstø, 2001). When teaching science, teachers tend to model as much as possible the practices of science but the use of evidence in school science, whether in illustrative or investigative work, is sometimes quite different from evidence used in socio-scientific issues and scientific research (Levinson, 2006; Gott & Duggan, 1995). Current emphases in science curricula around the world are upon scientific inquiry, the nature of science, and scientific literacy. For the most part, peer reviewed articles generated through the process of science are inaccessible to high school students due to specialized vocabulary, although elsewhere in this book adapted primary literature is used to engage students (see Chapter 3). The inaccessibility of scientific literature to those outside the culture of science is a well-documented phenomena (Hayes, 1992) so, traditionally, information given to students to support their learning in science is provided by the teacher in the form of class notes or dedicated textbooks. Such textbooks are usually written by science teachers together with scientists and reviewed for accuracy by scientists and teachers. The textbooks are either school- or teacher-selected and provide the science students with everything they need to know to pass a certain grade in school. However, we now are at an interesting time in science education because students are growing up and living in a digital age, living their lives through technology where print books are rarely part of their lives outside of school. Utilizing habits of students' life worlds is an important strategy that teachers can adopt to motivate them in school. Yet, even when teachers try to make this possible, such as with technology, there are often obstacles that hamper inquiry-based learning, such as firewalls and filters put in place to protect young people (Farris-Berg, 2008).

Our research explored two aspects of information literacy skills of high school science students making judgments about the validity of the information they read, which we have named 'reading for evidence'. The term 'information literacy' refers to the set of skills required to identify information sources, access information, evaluate it, and use it effectively, efficiently, and ethically. In high school it is not unreasonable to suggest that teachers would expect most of their students to already have the basic reading and writing skills to participate in their lessons. Is the same true for information literacy? Just how information literate are high school science students and how do they develop those skills? What exactly do students do when we set them information seeking tasks? How might the outcomes impact on their understanding of science? What implications are there for the teaching of science? These are some of the questions that we have explored through our research and that we consider here. The questions are related to what we can do to improve scientific information literacy—reading for evidence.

UNESCO (2009) describes information literacy as follows:

> Information literacy enables people to interpret and make informed judgments as users of information sources, as well as to become producers of information in their own right. Information literate people are able to access information about their health, their environment and work, empowering them to make critical decisions about their lives, e.g. in taking more responsibility for their own health and education (UNESCO, 2009, para 2).

This is not entirely commensurate with the notion of scientific literacy that is currently a key focus of science curricula worldwide. “Scientific literacy is the knowledge and understanding of scientific concepts and processes required for personal decision making, participation in civic and cultural affairs, and economic productivity” (National Research Council, 1996, p. 22). Norris and Phillips (2003, p. 225) provide a more helpful detailed analysis of concepts of scientific literacy:

- Knowledge of the substantive content of science and the ability to distinguish science from non-science;
- Understanding science and its applications;
- Knowledge of what counts as science;
- Independence in learning science;
- Ability to think scientifically;
- Ability to use scientific knowledge in problem solving;
- Knowledge needed for intelligent participation in science-based issues;
- Understanding the nature of science, including its relationship with culture;
- Appreciation of and comfort with science, including its wonder and curiosity;
- Knowledge of the risks and benefits of science; and
- Ability to think critically about science and to deal with scientific expertise.

We also have a host of other types of literacy such as digital literacy, technology literacy, critical literacy, media literacy, etc., and whilst some have their own specific contexts and definitions there is also some redundancy of terms (Sensenbaugh, 1990). Yet they all share the goal of making sense of the ever expanding universe of information. Given that information literacy transcends curriculum areas, it is important to ensure that any skill development is contextualized within the discipline. This is particularly important in science where evaluating information is an integral part of the nature of science. A new literacy is thus emerging that addresses this concern and that is scientific information literacy. Our work presented here contributes to an understanding of what this form of literacy might look like in the classroom.

There is a some research already in this field and our review of the literature on finding information shows that science students are challenged by evaluating the veracity and objectivity of information (Adams, 1999), and that they demonstrate significant preference for the internet and electronic resources over print resources (Barranoik, 2001; Jones, 1999; Shenton, 2007). In addition most students demonstrate poor search skills (such as difficulty selecting search terms, appropriately citing sources) (e.g., Barranoik, 2001; Fidel, Davies, & Douglass, 1999; Scott & O’Sullivan, 2005). Moreover, when working with information on the internet, high school students are unable to distinguish credibility in websites, that is, demonstrate insufficient higher level thinking when credibility or accuracy is being assessed (Brem, Russell, & Weems, 2001). When they do find information deemed to be relevant, high school biology students’ read scientific documents superficially (Brill, Falk, & Yarden, 2004) with minimizing effort as a key driver of students’ information seeking (Jones, 1999). Students also seek the ‘right’ answer and tend to judge relevance on the basis of convenient access and superficial criteria (Heinström, 2006). A number of papers have also explored how students make judgements about the evidence in media reports of scientific research (e.g., Kolstø, 2001; Norris & Phillips, 1994; Phillips & Norris, 1999; Ratcliffe, 1999). These papers show that students learn significantly about the nature of science from considering such reports but the criteria they use are based more on the processes of science than on the facts or content knowledge. These are particularly important observations given that much information on the internet about scientific topics lacks this contextual information and explains why more superficial criteria are being used by students.

Our research took place in the province of Alberta, Canada. The Alberta curriculum clearly identifies the importance of information seeking skills both from the Focus on Inquiry curriculum document (Alberta Learning, 2004) as well as within subject areas. For example, in our study we worked with students studying Biology 20 which has the following goals: "Students will be encouraged to seek and apply evidence when evaluating alternative approaches to investigations, problems, and issues; e.g., question arguments in which evidence, explanations or positions do not reflect the diversity of perspectives that exist" (Alberta Education, 2007, p. 16). Again, these skills are consistent with standard information literacy skills. Further, the biology curriculum includes the following expectations for high school students' experiences and learning:

- understand that scientific language is precise and specific terms may be used in each field of study;
- research, integrate and synthesize information from various print and electronic sources regarding a scientific question;
- apply given criteria for evaluating evidence and assess the authority, reliability, scientific accuracy and validity of sources of information;
- research, integrate and synthesize information from various print and electronic sources relevant to a practical question;
- research, integrate and synthesize information from various print and electronic sources relevant to a given question, problem or issue; and
- select information and gather evidence from appropriate sources and evaluate search strategies (Alberta Education, 2007, pp. 8–10).

Moreover, the Alberta curriculum supports development of information and communications technology (ICT) skills (Alberta Education, 2008), which are absolutely consistent with information literacy skills as understood more broadly. We thus see an interesting paradox where the Alberta high school curriculum emphasizes the need to develop information literacy skills that are integral to the process of science, yet in science subjects little emphasis is given to information literacy or connection to science inquiry and the nature of science.

Full details of the research methodology from our study can be found in Julien and Barker (2009). The context of the research was a class task on finding information on Biomes rooted in the Biology 20 program of studies. We asked students as part of this task to reflect on the information seeking task in addition to interviewing students about the process.

The two key areas that we want to explore in this chapter are the use of textbooks and the internet as sources of information for students. The research literature suggests that many students are motivated to choose strategies that ensure they can complete the task in the shortest possible amount of time. Indeed students in our study expressed similar views about not wanting to waste time, and as a result the internet was the favourite method for finding information, followed by class textbooks. We suspect that this is because it is easier to cut and paste digital information into an assignment, but no one admitted to this possibly because of plagiarism issues!

## CLASS TEXTBOOKS

In Alberta, there is a heavy dependence on the use of textbooks in science classrooms. Textbooks used in schools are approved by the province on the basis of a match with outcomes described in the Program of Studies. Schools and teachers then select specific books from the list of approved textbooks; students usually have access to one textbook in a subject area. In the development of these authorized textbooks, content is reviewed for accuracy and appropriateness by scientists and teachers and these experts are listed at the front of the book. So here we have an interesting situation of information in the form of a textbook which already has had several stages of evaluation, validation, and approval before getting to the classroom.

In our study, a number of students expressed a desire to use the class textbook as the main source of information despite not finding it easy to use. These students were making a crude cost-benefit analysis based on the fact that they assume that all the material presented in the textbook is relevant so they don't need to evaluate it and sift through irrelevant material, which wastes time. Students told us that they had absolute confidence in everything in the textbook because their teachers and schools recommend it to them and they have faith in the teacher and in the school. Andy said, "Well I used it [a textbook] because I knew it would be reliable. If the school would give it to us and it not be reliable...then that would kind of be defeating a bunch of purposes." So this presents an interesting issue for science teachers. The evaluation is vicarious having assumed to have been done by teachers, the province, and experts who have reviewed the material for accuracy and relevancy. Whilst many students are not aware of the behind-the-scenes evaluation, they are basing their trust in the textbook on the trust they have in their teachers. Here is an example of students accepting knowledge without question because of unconditional trust in the textbook, in the teacher, or in both.

Teachers could ask their students: "Would a research scientist studying antibiotic resistance in bacteria use a school textbook as a source of information to plan their work and, if not, why not?" While this question might seem quite ridiculous and the answer obvious, it will facilitate a discussion about information literacy, the differences between information and evidence, the rapidly changing nature of scientific knowledge, thus the nature of science. Clearly the purpose for using the information is a key factor in determining the level of evaluation given.

A useful extension task would be to compare the peer-review process in the development of textbooks, where secondary information is reviewed for accuracy and appropriateness, with peer review in scientific research journals.

The future of textbooks in science classrooms is unclear. Farris-Berg, who reported for Project Tomorrow on the next generation in science education, indicated only one in five students saw a role for textbooks in future science classrooms (Farris-Berg, 2008). There is no doubt that the trend for using electronic textbooks instead of print will continue, but it is unclear whether there will be any radical change in how the information is reviewed and selected. In addition, how a textbook is used in science class is a pedagogy that is under-researched, despite its implications for our work. From our own observations of science classrooms we regularly see teachers ask students to read chapters silently or out loud in round-robin style without any consideration of the nature of the information. Neither of these strategies will help students better understand scientific concepts (Walker & Huber, 2002) or read for evidence. What is clear is that we need to get students to be critical of textbooks and print information irrespective of authorship and explore what we mean by scientific evidence. A useful activity is to compare old textbooks with new on a specific topic to demonstrate just how much (or little) scientific understanding has changed over the years.

## INTERNET

Findings from the in-class task in which students had to find information on Biomes were generally consistent with previously published research. Overall, even though students were given access to a wide range of information sources, the internet was the most frequently used source for the students' research (59% of sources identified). Google™ was the most used search engine to access either specific sites, such as Wikipedia, or in general searching. The dominance of Google™ in students' responses was noticeable. Students regarded Google™ as being 'the' internet and used the two terms interchangeably. In addition, Google™ as a source of information was used indiscriminately for all sources of information for school and home (i.e., for academic and for personal information seeking) and great confidence was placed in the web sites that Google provided, with many students simply using the first site listed from the search. Chandra stated, "I just Googled it and then I compared between different pages to see how accurate it was and then I went with the one that showed up the most". The largest proportion of students' responses to why they turned to the internet most often (35%) focused on perceived relevance of information found (i.e., answers the task questions). Accuracy of information was identified by comparing multiple resources for consistency in information provided (42%). Students mostly looked at the first three sites from a Google™ search and, if the information in these three sites was comparable, then this gave the students a measure of validity. Carrie noted, "I usually just click the first one and read it, and then I'll click a couple more and if they all say kind of the same thing then I'll keep that, because you're getting it from multiple sources, so chances are it's real." Repeatedly, credibility was judged by noting that references were provided (48% of respondents). Relevance was assessed according to whether the information found answered the task question to be addressed, that is, by topical relevancy (41% of responses). Students reported skimming information for relevant key terms in order to assess relevancy.

Students in our study indicated that they preferred to use the internet because it is convenient and familiar, and that searching by key word is easy. As Natasha states, “Well, I’m – it’s more reliable than going to the library and trying to find a book..., ‘cause it takes less time.” Robert noted, “Well it’s much more convenient than, you know, you want to do something else with your time. If you get the information right here, you can finish the task quicker.” Kendra stated that the internet is “a lot more easy to access whereas the library and the textbooks we have to go to the library.” However, their searching skills are quite unsophisticated. In general, students search by pasting the assignment question or task directly into the search box. They scan the first three or four web sites that appear for matching key words, and the content of these top sites are compared for consistency. Interestingly, Wikipedia is used and liked by many of the students, although there was an uneasy tension as students commented that Wikipedia is often the first webpage listed from a Google™ search, but it is widely judged by them as not being a valid source of information. Jimmy said, “Wikipedia was just another place to compare because Wikipedia is an open source. And then so, being an open source it is not exactly always reliable.” Head and Eisenberg (2009) also found that students like to go to Wikipedia first as this collaborative, community-based online encyclopaedia gave students the big picture and language contexts. Their students described Wikipedia as their “first go-to place” because Wikipedia entries offer a “preview” and provide “a simple narrative that gives you a grasp” and “can point you in the right direction,” and “helps when I have no idea what to do” (Head & Eisenberg, 2009, p. 11).

The trustworthiness of information that students accessed was predominantly viewed in terms of the site or resource including domain name rather than by evaluation of the content. For example, university sites were mentioned as being accurate, with some students viewing university sites as reputable and reliable using information from these sites for school purposes. However, examples given of university sites were from the U.S. rather than local Alberta institutions. For example, Allison said, “I use the University of Berkeley site cause they’re a generally trusted university name and you can assume that you can trust the research they’ve done.” However domain names such as “angelfire.com” were considered by one student to suggest unreliability. Evaluating information on websites by examining domain name only is a risky practice; students need to be better equipped at evaluating content. If you draw comparisons with making judgments about the accuracy of information in a book based on the title of the book then the basis for making that judgment is more obviously flawed.

## DEVELOPMENT OF INFORMATION LITERACY SKILLS IN SCIENCE

The largest proportion of participants stated that they learned how to select information for science classes by experience with non-science school projects

(38%), and through non-academic personal experience (29%). Friends and family were frequently mentioned as those from whom the students had learned their skills. Overall, when asked directly, students expressed confidence in their information-finding and evaluation skills. Eva stated, “I guess just basically from years of experience I can tell whether or not something is reliable or not reliable.” Robert said, “If Wikipedia’s not first, then I just go with the first site Google™ gives me.” This concurs with Head & Eisenberg (2009) who found that most students have developed strategies, techniques, and workarounds through trial and error and designed their own methods that sometimes, but not always, help them find content when searching for information.

Students reported that their primary search strategy is keyword searching. While this approach is useful for new vocabulary (e.g., “podcasting”), when there is no thesaurus, when searching is resulting in few hits, or when a known item is sought (e.g., specific author), there are significant limits to the value of keyword searches. The students in this study are unfamiliar with the benefits of searching by controlled vocabulary to improve comprehensiveness and precision. In addition, these students are apparently unaware of how search engines identify potentially relevant sources. Thus, the limitations of searching by Google™, and of searching with only one search engine, are not understood.

The school in the research study was a very multicultural school with a Mandarin language program. One student for whom English was not his first language and who was a recent immigrant to Canada could not easily articulate what he had done to find information but had used the internet using English key words rather than in his native Mandarin language.

Overall, the students revealed unsophisticated evaluation skills. Understanding of critical evaluation criteria such as authority, accuracy, objectivity, currency, and coverage, was not evident from the students’ comments. Not one student used language that was commensurate with the nature of science, for example, ‘evidence’, ‘reliability’, or ‘validity’.

## STRATEGIES FOR TEACHERS TO HELP STUDENTS FIND INFORMATION

It is clear that despite the unambiguous curricular mandates to develop information literacy skills, actual skill levels in the students in the study were underdeveloped. The “Focus on Inquiry” document (Alberta Learning, 2004), which explicates sound information-searching skills, is clearly insufficient to ensure that students are developing these skills. Actual classroom practices and teachers’ understandings and attitudes were not explored in this study, so their relationship to the results reported here remain uncertain. It is possible that teachers believe that students already have these skills, or perhaps that they themselves lack sophisticated skills and are therefore unable to provide guidance to their students. One reason for the lack of emphasis is that information-seeking skills are not directly assessed in the provincial exams. So, even when such objectives are listed in the curriculum they are unlikely to be taken seriously by teachers. This observation was pointed out by an Alberta science teacher at a science council professional development workshop where this study was discussed. Such assessment-led teaching is not confined to Alberta and is a common phenomenon worldwide. In order for content or skills to be taken seriously they need to be assessed. However, we do believe that this is a missed opportunity, particularly for science teachers.

Science lends itself very well to discussions about the construction of knowledge, accuracy of information, and evidence the students may find on the internet. For example, the tentative nature of scientific knowledge is a critical issue to address when developing information-seeking skills in science. A student in our sample who used his "grandmother's encyclopaedia" to find information for all school tasks and personal interests irrespective of the topic, had not considered why he might need to use more contemporary resources. The 11th edition of Encyclopaedia Britannica published in 1911 presents quite a different view of the world than we see today. The word 'Biome' (the topic of the students' science task) is not even included, and older books contain many descriptions of biological phenomena which would today be considered incorrect, for example, in pre-1980 books, the structure of the cell membrane. In order to counter these concerns, teachers could present relevant scientific information from historical and contemporary resources to demonstrate how knowledge and understanding have changed and why recent resources have the potential to be more accurate. An excellent example of such a task is presented by Warren (2001) who uses scientific knowledge about scurvy from a number of periods in history. This role play requires several students each to act out the role of a medical doctor at a specific time in history. They have to make a diagnosis and prescribe treatment for scurvy based on the scientific information and evidence that would have been available to them at that particular time in history. The survival rate of their patients is clearly linked to the scientific information demonstrating that we need to use the most recent evidence we have available to us.

As students are unaware of how search engines work and the way in which websites are ordered it would help if teachers drew attention to this. Of concern is the dominance of Google™, which is revered as *the* way to find information without any question or concern about underlying marketing strategies and economics filtering information. A simple task would be to present a search to the class using two or more different search engines to demonstrate just how serendipitous (or not!) the process is and to provoke discussions about the activities of information brokers such as Google™. Google™ ranking is based on popularity as determined by internal links (so Wikipedia is highly ranked). Some sites pay to be indexed (and pay for ranking), for example, the right column list in Google™, and students need to be alerted to the impact of this on the information they obtain. Other points to alert students to are that every word is indexed and order matters. Ranking algorithms are secret but first lines, titles, metadata tags, top of page, linked words, number of links to page are part of the process. It is widely known that abuse and manipulation are possible and that the domain (geographic location) matters—and that there is censorship in some countries. Some other advice that could be provided to students for searching:

- Look for the name of the author or organization
- Go to the home page of the host site to find out about the organization
- Use a search engine to find more information about the author
- Check for date of last modification (on page or using browser's "Document Info" or "Properties")
- Use the URL as a clue to authority
- a ~ indicates a personal page
- note domains (edu, gov, com, net, org, etc.)

We also found that students become overwhelmed when faced with 3 million webpages from their search term. Most students were unaware of Boolean Operators named after George Boole a 19th Century Mathematician. The main Boolean operators are:

- AND, which finds only those pages with both terms;
- OR, which finds pages with any one or any combination of search terms;
- NOT, which finds articles that exclude one or more terms (see Cohen, 2011).

Finally a common misunderstanding is that searching occurs on live sites but this is not so: the searches are of indexes, so information can be dated.

We see that overall students gave less emphasis to the process of finding information than the end product of the search. Indeed, Barranoik (2001) too found that biology high school students showed that they were more concerned with the content than the process. In our study many students found it hard to recall precisely what they had done or why, despite specific questions addressing the process in their assignment. Rarely are such questions asked of students despite increasing evidence of the benefits of metacognition (Brem et al., 2001). The ultimate goal was for 'information to go', finding precise information in the easiest way possible and in the shortest amount of time. Thus, we recommend that teachers give more emphasis to the process of finding information by perhaps assigning marks for process as was done in the task set for this research.

Students' primary search strategy was through the use of natural language (keyword) searches and this strategy is particularly useful:

- for new vocabulary (e.g., "podcasting");
- when there is no thesaurus;
- when you're getting few hits; or
- when a known item is sought (e.g., specific author).

However, students should also be helped to go beyond keyword searching by using controlled vocabulary, which are subject terms used to identify records in a uniform manner. For example, in the ERIC database, "library instruction" is the official subject term used for “bibliographic instruction” and “library orientation.” The advantages of controlled vocabulary are:

- Facilitates gathering like items (brings together documents about similar concepts even if those concepts are identified by synonyms);
- Improves comprehensiveness of search (missing a critical synonym is less likely);
- Improves precision of search (e.g., search for “students, medical” will exclude all other students.
- Gives insight into ambiguous terminology: MERCURY (Roman mythology) vs. MERCURY (element);
- Broadens understanding of available terminology.

## INFORMATION LITERACY AND SCIENCE INQUIRY

The connections between information literacy, scientific literacy, and science inquiry seem to be under-utilized and we argue that more attention to making these connections could help promote a better understanding of the nature of science. However an important point here is that finding, evaluating, and using information are critical parts of how a scientist conducts research inquiry. Thus, if school science inquiry models the practices of scientists, then emphasis on this part of the process could also enhance an understanding of the nature of science. Science inquiry is often misunderstood as being the same thing as the nature of science. Much of the confusion can be attributed to the variety of approaches advocated for science inquiry. For example, Crawford (2000) emphasized that teachers’ ideas and practice about inquiry are varied and complex. The starting point of inquiry is also ambiguous. For some teachers, a problem or question is given to students. With only a question or problem to go by, the students may begin science inquiry with sparse and disorganized background knowledge. Therefore, they should first conduct background library or internet research (Windschitl, 2008). Windschitl views such information-seeking tasks as being ‘supporting activities’ of inquiry, which help prepare students to participate more meaningfully in the core activities of inquiry by acquainting them with necessary concepts, ideas and skills (Windschitl, 2008). Whether the information seeking is seen as part of the inquiry process or supplementary to it, science classrooms where students follow an inquiry model of learning are ideal in which to develop and refine information literacy. In a science context, the parallels of information seeking with science inquiry could be to the benefit of teachers and students, each one having the potential to reinforce the other with the additional bonus of helping to understand the processes of science. The whole process of information seeking is remarkably similar to the stages of science inquiry, despite being considered by Windschitl (2008) to be a subset or complementary activity to science inquiry. Introducing information-seeking tasks in the context of the work of scientists may be a helpful strategy. For example, would scientists working in stem cell research use their grandmothers’ encyclopaedia to find information to help them plan a new experiment? This sort of question could lead to useful discussions about the nature of scientific knowledge.

Presenting the task as a scientific question or encouraging students to pose a question to answer is a good way to start. Teachers might consider using a constructivist approach, eliciting students' prior understanding about the topic. One of the possible ways in which information seeking may be related to science inquiry is presented in Table 2.1. Such a side-by-side comparison helps reinforce the processes of scientific inquiry in addition to information seeking. Alternatively highlighting the role of information seeking as a pre-cursor to scientific inquiry (Windschitl, 2008) would be equally as useful.

*Table 2.1. Links Between Information Seeking and Scientific Inquiry*

| *Information Seeking Task* | *Science Inquiry*[a] |
|---|---|
| Goal: Finding credible information to meet an identified need | Goal: Developing defensible explanations of the way the natural world works |
| Elicit prior knowledge | Elicit prior knowledge and organize what we know and what we'd like to know. |
| Plan search strategy (identify key words, appropriate synonyms and combinations, identify possible credible sources) | Generate hypothesis |
| Execute search strategy (iteratively, according to results) | Seek evidence to support or refute the hypothesis |
| Evaluate information found according to standard criteria | Construct an argument |
| Communicate or present results as required | Communicate findings |

[a] Partly adapted from Windschitl (2008).

### *Cultural Context*

We also need to consider that evidence is constructed through a western world view of science. As we begin to recognize and value the role of traditional knowledge systems in our curriculum, we know that some cultures value the written word less than oral traditions. For such cultures, reading for evidence is likely to be an alien concept. What is more relevant is the notion of reading the environment that is considered in Chapter 5. Given the multicultural context of many of the world's classrooms, a useful strategy would be to encourage students to search for information in their first language rather than the language that is predominantly used in the classroom. This opportunity could be used to highlight any differences that may arise from searching in different languages, and to consider the significance this has for science. Searching in their first language may help students improve understanding in specific content areas and would give the students a break from the constant demands of having to translate everything. In addition, such an approach may enable inclusivity of parents or guardians in the students' school work.

Moreover a focus on written information is also restrictive with regard to inclusion of traditional knowledge and aboriginal world views where much of the information is visual or oral. As oral and visual traditions are integral to an understanding of traditional knowledge, it is useful to discuss similarities and differences in recording of knowledge and information between western world science and traditional world views. Indeed the Alaska Native Science Commission (ANSC, 1994) website provides such a comparison.

## *Textual Scientific Inquiry*

The fact that students evaluate information superficially led us to develop a teaching prototype for use in secondary classrooms that facilitated a science inquiry approach on a piece of textual information. The rationale was to enhance students' understanding of science inquiry, to broaden the range of inquiry approaches that might be considered in the science classroom, and to develop more sophisticated scientific information literacy skills in students. Researchers such as Kolstø (2001), Ratcliffe, (1999) and Norris and Philips (2003), who have worked with young people dealing with media reports of science, have indicated that some of the criteria students use to make judgments about information are based on the ways in which the research was conducted and by whom. These criteria are more to do with the processes and nature of science than with the information *per se.* Levinson's (2006) work with teachers and controversial socio-scientific issues highlighted a need for: "facts; the reliability and validity of evidence; and the contrast between facts and values" (Levinson 2006, p. 247). We wanted to focus on the information itself and not necessarily on how it was constructed, so we focused on the distinction between scientific facts, misconceptions and values and how these are used to inform and educate students about a range of socio-scientific issues.

We initially provided students with some broad descriptions of what facts, misconceptions and values are. We indicated that factual statements attempt to describe. Thus, a fact is a verifiable statement of what is true. For example, the estimate of North Atlantic Harp Seal population in Canada in 2011 is 9 million based on population estimates. Another definition is that statements are facts if they "remain stable when challenged" (Bingle & Gaskell 1994, p. 197). Factual statements (which can be specific, general and even theoretical) attempt to describe, but not evaluate the worth of a thing or action. (Note that some theorists believe that scientific facts are not completely value free, but this refinement was not considered for the purposes of this study.) Also we encouraged students to think about the difference between a scientific fact that is verified by the scientific method, and descriptions which are a 'matter of fact' but are based on informal evidence such as a personal observation. We proposed to the students that a misconception (sometimes referred to as a myth) is sometimes treated exactly the same as fact because a myth is what people think is fact. How they arise is unclear but it may be based on incomplete evidence, partial truths, or being misled through advocacy groups or the media. Finally, we suggested that values are opinions about how things should be and place value (positive or negative) on the way things are (or were, or could be). Values cannot be proven right or wrong by scientific methods. An example of such a value is, Seals should not be hunted. We also encouraged students to recognize that scientists who have studied the issue, have scientific qualifications, and may even be described as 'expert', do not necessarily have values superior to anyone else. There are often no right or wrong answers to public issues and more often than not scientists will not make value statements when doing science because they are stepping outside the boundaries of science.

Our prototype teaching method used content analysis, which has a long history as a research method used to measure and analyze textual material. Content analysis is used in media studies to measure some aspect of the content of written, spoken or published communication by systematic, objective, and quantitative analysis. It is a means of trying to learn something about people or organizations by examining what they write. Neuendorf (2002) provides a helpful definition:

> Content analysis is a summarizing, quantitative analysis of messages that relies on the scientific method (including attention to objectivity, intersubjectivity, a priori design, reliability, validity, generalizability, replicability, and hypothesis testing) and is not limited as to the types of variables that may be measured or the context in which the messages are created or presented (p. 10).

It assumes that what is written reflects the behaviour and attitudes of the author or the organization. In our teaching prototype, we used it as a teaching tool rather like we use scientific method as a teaching tool in scientific inquiry. Essentially, it follows an inquiry model so the strategy has the potential to reinforce students' skills in scientific inquiry. Text or images are used as a source of data that can be measured using a series of parameters recorded in a table known as a coding frame. The parameters in the coding frame can be provided by the teacher or developed by the student depending on the type of inquiry approach being used. To differentiate between levels of textual inquiry we proposed a model based on Bell, Smetana, and Binns (2005). As can be seen from Table 2.2 and Table 2.3, the amount of information provided to students decreases as the inquiry level increases from level 1 to level 4.

The idea was to introduce the activity to students at a level matching their previous experience of science inquiry and ability and to provide progression through increasing sophistication of the technique. To familiarize students with the approach, we suggested starting with level 1 then moving through the levels as students gain confidence in the approach. The model can also be used as a differentiation tool in the classroom to provide different tasks for a range of abilities.

*Table 2.2. Levels of Textual Inquiry*

| *Inquiry Level* | *Description* |
|---|---|
| 1. Confirmation | Teachers present a question, a coding frame and results. Students interpret the results and make conclusions. |
| 2. Structured Inquiry | Teachers present a question and a coding frame. Students collect data, interpret the results, and make conclusions. |
| 3. Guided Inquiry | Teachers present a question. Students collect data using coding frames that they have developed. They interpret results and make conclusions. |
| 4. Open Textual Inquiry | Students investigate questions that they have formulated. Students collect data using coding frames that they have developed. They interpret results and make their own conclusions. |

*Table 2.3. Information Given to Students in Textual Inquiry*

| *Level of Inquiry* | *Question* | *Coding frame* | *Data* |
|---|---|---|---|
| 1 | ✓ | ✓ | ✓ |
| 2 | ✓ | ✓ | |
| 3 | ✓ | | |
| 4 | | | |

### *Selecting Appropriate Materials*

The first step was to collect some contrasting pieces of information that address a socio-scientific issue that was being explored in class. Two is the minimum number so that comparisons can be made. In our pilot studies some teachers used three pieces of information. As confirmation that teachers and students are swamped by too much information we found that this was one of the most difficult parts of the task. We encouraged teachers to use materials they had selected so that they would be relevant to the context of their schools and be appropriate for their students. We found that the majority just wanted to use materials we had provided. They could find lots of information but it was discerning the contrasting material that proved to be too big a challenge and too time consuming.

We thus provided three sources of information for two contexts (Edmonton Sun, 2006; Fink, 2007; Fisheries and Oceans Canada, 2006): the Seal Hunt and Climate Change. Considering the seal hunt case, we asked the students: How are scientific evidence and opinions/values used to promote or reject the seal hunt? The focus was to get students to think about the types of scientific evidence and facts used in the discussion of the issue and the range of value statements. To help them on their way we asked them to brainstorm both pro-hunt and anti-hunt reasons (See Table 2.4).

*Table 2.4. Examples Provided by the Students*

| *Pro-hunt* | *Anti-hunt* |
|---|---|
| Too many seals | Cruel/inhumane |
| Provides jobs for people | Hunt is unsustainable and seal populations will fall |
| Food for local people | Most people don't want the hunt |
| To allow more cod | Seals don't eat much cod |
| Provides pelts for lucrative fur industry | Synthetic clothes are better |
| Provides penises for traditional herbal medicine | There's no scientific evidence in support |

We then set the context by asking the students to think about types of scientific evidence that would support of refute these arguments: data on seal populations; data on cod population; research on pain and suffering by seals; and opinion surveys. We set three sequential tasks using content analysis. For the purposes of the pilot we provided coding frames (data tables) for them.

*Task 1 Quantifying facts and opinions.* We instructed the students as follows:

> You are provided with 3 different sources of information found on the internet on the Canadian Seal Hunt. The sample materials represent newspapers, Canadian government, and anti-hunt groups (International Fund for Animal Welfare, IFAW). With your knowledge of the seal hunt and knowledge of what facts and opinions are, do you think that there would be a difference in the number of facts and opinions in each of the different sources.
>
> Method- Examine each document and count the number of science facts and opinions in each. Choose a method which allows you to count facts and opinions separately. For example, underline the facts and circle the opinions or use coloured highlighter pens. You can use a coding frame such as the one below.
>
> | | Item 1 (Gov) | Item 2 (IFAW) | Item 3 (News) |
> |---|---|---|---|
> | Number of facts | | | |
> | Number of opinions | | | |
>
> Significance? What do your results show?
>
> Conclusion? Can you make any conclusions based on the data and small sample?
>
> Further studies? What would you need to do in order to confirm or refute your hypothesis?

This task clearly focused on differentiating between facts and opinions. There are some challenges with this approach given that 'facts' that inform socio-scientific issues can be drenched in values, highlighting that presenting such a dichotomy might distort students' understanding of the way in which evidence is generated and interpreted (Levinson, 2006). However, in our follow-up work with students, the task of differentiating between facts and opinions seemed to be incredibly satisfying leading us to believe that this is an important step upon which to build more discriminating and specific scientific information literacy skills. For example this grade 10 student still had naïve understandings of fact, opinions, and proof:

> The most useful activity is reading through 3 articles and deciding on whether the information is a fact or opinion. This helped me decide if there is proof or not. If there is a noted source, it was considered fact but if not was an opinion.

*Task 2 Same story, different facts*. For this task, students were instructed as follows:

> Now examine in the table how the scientific facts or evidence vary in the different documents.

| *Evidence* | *Item 1 (Gov)* | *Item 2 (IFAW)* | *Item 3( News)* |
|---|---|---|---|
| Population data Harp Seals 2004 | 5.8 million | 5.82 million | 6 million |
| Number of Harp Seals killed 2005 | No information | 389,512 | No information |
| Government quota 2006 | No information | 335,000 | 559,000 |
| Value of seals 2005 | $16.5 million | $51,710,145 | $6 million |
| Pelt value | No information | $13 jacket pelt<br>$22–55 beater pelt<br>$7 adult pelt | $70 |
| Population change | Triple population size of the 1970's | No evidence of rising population<br>Currently stable | No information |
| Opinion polls | Ispos Reid 60% favour | Environics 69% opposed | No information |

> Questions to consider:
>
> Do some of the facts vary across the three categories?
>
> If so, why might this be so?

Students found this exercise the most surprising. They learned that what might appear to be exact statistics (e.g., government quotas) could have different figures depending on the source. They also connected the activity with how they may present their own data in traditional labs in school and the importance of accuracy. One Grade 10 student said, "My labs will be more valid because I will be comparing my findings to more accurate data."

*Task 3 Informal evidence.* Students were guided as follows:

> Some of the articles may use what would be regarded as 'informal evidence', that is, considered as a common sense view of the issue or individual observations. These could not be counted as scientific evidence because they have not been tested or thoroughly investigated but have slightly more value than pure opinions because they are based on reality.

| *Evidence* | *Item 1 (Gov)* | *Item 2 (IFAW)* | *Item 3( News)* |
|---|---|---|---|
| Helping cod stocks | No information | There is no evidence that culling harp seals will benefit commercial fisheries | No information |
| Population change | The harp seal population size is healthy and abundant | There is no scientific reason to cull Harp Seals | "Seals aren't out here"<br>"Hunters hunt for scarce animals" "High mortality due to climate change" |
| Cruelty | The club or hakapik is an efficient tool designed to kill the animal quickly and humanely | Canada's commercial seal hunt is unacceptably cruel | "Several seals shot and left to die on the ice"<br>"A number of pans …were empty and stained with blood" |

We found from using the prototype in schools that students really enjoyed doing something active with the text rather than reading and discussing. They were motivated by highlighting, counting and entering data into a table or spreadsheet and they also enjoyed the fact that it was quick to do and they had something tangible to show for their consideration of the material. Reading and discussing does not leave students with any record of their analysis, leaving them feeling that nothing has been achieved. Most students were surprised that facts might be different in different sources particularly when they might have been previously deemed credible by using superficial criteria such as type of organization. They liked using web-based resources and working collaboratively on the tasks.

One of the greatest benefits commented on by virtually all of the students and teachers was that the activities enhanced an understanding of scientific inquiry.

> In all honesty, this exercise was the most useful as it forced us to critically analyze the truth in each and every sentence. We did something similar in English class and it really widens your eyes and makes you notice that not everything you read in an article is 100% true. We learned that it's much more difficult to prove opinions than facts. (Grade 10 student)

> The topic has greatly improved my understanding of scientific inquiry because it gave me clear information in sorting out if the statement is a fact, misconception, or opinion. It also made me understand that comparing issues with a few other articles is necessary for scientific inquiry to see if it's valid. (Grade 10 student)

> Before the topic I didn't know what scientific inquiry was but now I do. (Grade 10 student)

The teachers involved in the activities also recognized the contribution of the analysis to an understanding of scientific inquiry and thus reinforced an understanding of the nature of science. However they did not believe that an inquiry approach generally helped students score better in the provincial exams. Using the activity as an open-ended inquiry was too time-consuming for a classroom-based task, but teachers thought that it was a very helpful scaffold for developing critical thinking skills.

> I think it helped them understand science inquiry. I think it did for some of them. It makes them a little bit more thoughtful and makes them think a little bit more about what they are doing in science rather than just information overload. Especially on topics such as this that they are going to see again in social studies down the line and maybe further down the line. (Teacher Science 10)

So when reading for evidence, science students should be encouraged to read and count! Reading as a task is unlikely to develop critical thinking skills and a science inquiry approach using content analysis helps students really differentiate between facts, myths, and values and thus read for evidence. However, whilst it is helpful to highlight the distinction between facts and values what is more important is to focus on examining all sources of knowledge critically (Levinson, 2006).

## CONCLUSION

It is perhaps inappropriate to expect teachers to deliver and interpret curriculum in areas where their own skills require significant development. The complex task of supporting the interpretation of evidence in controversial issues needs to be part of a teacher's repertoire. Yet, teachers give priority to day-to-day functions of teaching over reflection about the nature of evidence in controversial issues (Levinson, 2006). Indeed, Levinson goes on to cite Bartholomew, Osborne, and Ratcliffe (2002) who found that teachers, when teaching controversial issues in science perceive their primary function as dispenser of knowledge and provider of factual information (Levinson, 2006). Moreover, Williams and Coles (2007) interviewed teachers in the United Kingdom and found that teachers lack information literacy skills, especially searching and evaluation skills. Asselin (2005) found that a lack of time to teach information literacy is a significant barrier for teachers. We are at a curious point in time when many students have better ICT skills than their parents or teachers and this can be intimidating. There are some resources for teachers already. Some science resources, for example, Ebenezer and Lau (2003), fail to address the information literacy skills highlighted in this chapter including the necessity to explore the nature of scientific evidence when reading scientific information. Undoubtedly, information literacy needs to be explicitly addressed in the classroom. In scientific disciplines, scientific literacy and information literacy are inextricably linked. Teaching students skills in searching for and evaluating information within a science inquiry framework has the potential to help them understand better the nature of science and the nature of scientific knowledge. In addition, it will help them learn more widely applicable information literacy skills for use in daily life. The value of these skills is unchallenged, but significant challenges to inculcating them remain.

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# 3. READING FOR EVIDENCE THROUGH HYBRID ADAPTED PRIMARY LITERATURE

## INTRODUCTION

In making a case for adapted primary literature (APL) in science classrooms, Brill, Falk and Yarden (2004) outline a wide range of opportunities afforded to students, including: understanding the rationale for research designs and procedures, exploring the important connections between chosen research methods and research questions, increased familiarity with scientific communication and the language of science (e.g., expressions of uncertainty and appeals to authority/evidence), practice in questioning and critiquing the methods and findings of researchers, exposure to common designs and procedures used in different areas of science, and an introduction to the ongoing nature of scientific research. These opportunities are seen to arise because scientific texts, such as APL, contain both a) substantive scientific content and b) a reasoning structure meant to represent elements of the underlying reasoning structures of science. These scientific texts both illustrate and require: analysis, interpretation, comprehension, and critique. To read and understand scientific texts, is to read and understand something of the ways in which scientific knowledge is generated (e.g., Norris & Phillips, 2003). In particular the social norms, including acceptable communication practices and argumentation, are strongly represented in text and largely inaccessible to students without it (Fang et al., 2008). Authentic scientific texts, in particular, can provide an important opportunity for students to develop a nuanced understanding of epistemological aspects of science. To explore these relationships further, this chapter examines the particular value of hybrid adapted primary literature (HAPL) (writing that integrates adapted primary literature with narrative writing about science and scientists) for extending the benefits of APL beyond high school science and into the elementary classroom, in particular exploring the possibilities for representing and teaching about epistemological practices related to evidence in Grades 5 and 6.

## TEXT AND THE INQUIRY SCIENCE CLASSROOM

The message at the core of most English language science curricula is that science education should actively engage students in meaningful inquiry. The way this is communicated can give the impression that inquiry science education means predominantly hands-on active work. For example, the Pan-Canadian Science Framework states, “Students learn most effectively when their study of science is rooted in concrete learning experiences, related to a particular context or situation,

*Stephen P. Norris (Ed.), Reading for Evidence and Interpreting Visualizations in Mathematics and Science Education, 41–63.*

and applied to their world where appropriate" (Council of Ministers of Education, 1997, p.7). Reading is frequently referred to only in the context of textbook reading and content learning, where it is placed in opposition to inquiry science: "Science teaching must involve students in inquiry-oriented investigations in which they interact with their teachers and peers. …The perceived need to include all the topics, vocabulary, and information in textbooks is in direct conflict with the central goal of having students learn scientific knowledge with understanding" (National Research Council, 1996, pp. 20–21). At best, especially in elementary science, reading about science is often seen as a pathway to literacy (e.g., students need to learn to read informational text), but it still is seen as something extra or other to inquiry science. At worst, reading can seem antithetical to inquiry, where reading is characterised as only textbook or worksheet reading. Reading and text are, however, essential for inquiry, offering access to social norms and epistemological practices of science. Because of the forms that scientific text takes, it should be central in encouraging and supporting student inquiry in school science.

### *Textual Representations of the Evidence Practices of Science*

From Dewey and Schwab to contemporary science educators, there's been recognition of tight interconnections between understanding that science itself is inquiry and approaching student learning of scientific concepts from an inquiry perspective. Flick and Lederman, in their introduction to the volume *Scientific Inquiry and Nature of Science*, are clear to emphasize the intertwined nature of these two goals and how a thorough understanding of the latter depends on the former. They argue that "It is one thing to be able to focus on a scientific question [e.g., to do inquiry to learn scientific concepts], for example, where does salt go when dissolved in water, and quite another to recognize that question as part of a much larger process of building scientific knowledge" (Flick & Lederman, 2004, p. xi). In the context of this example, there will be no definitive single piece of evidence to support the desired concept that the salt is distributed, on a particle level, throughout the water. Understanding the value of different forms of evidence and the processes of making decisions based on the weight of several different types of evidence are needed to make this a valuable student inquiry. An important scaffold therefore is an epistemological understanding of science—of which evidence is acceptable for creating an explanation and how different pieces of evidence come together to support a broad and underlying explanation like the particulate nature of matter. If this is the case, though, why not stop at explicitly teaching concepts related to the nature of science? Why is text important?

Authentic scientific texts are important because, as a complement to the explicit lessons that teachers can provide about nature of science related ideas, they can provide a window into and immersion in the social and cultural practices of science (Norris & Phillips, 2003). In making comparisons between the discourse patterns of different academic disciplines, including physical and biological sciences, Hyland (2004) makes a very strong case for the importance of the text itself for what it says about the priorities, beliefs and values of those who write it and the communities to which they belong. The writing conventions and practices are themselves a window into the culture: “The rhetorical conventions of each text will reflect something of the epistemological and social assumptions of the author’s disciplinary culture” (Hyland, 2004, p. 11). He goes even further to say that the texts and the communities are co-constitutive—not only do disciplines shape their ritual texts, the texts (and the values embedded in them) also make the disciplines what they are. Scientific texts therefore have a lot to say to students about the epistemological culture of science, of science as inquiry.

This is not of course to say that texts are a direct representation of what scientists do. Schwab (1962, p. 81), somewhat famously described them as “unretouched specimens of enquiry” but research has repeatedly shown that scientific texts instead reflect norms of scientific writing rather than direct descriptions of research processes (Elam, 2004; Myers, 1992). But those norms themselves represent epistemological values, beliefs, and ideals.

### *Which Elements of Scientific Text?*

I am focusing on the elements of text that represent practices related to scientific evidence, referring specifically to two types of language: epistemological language and metalanguage. Epistemological language is used by scientists to construct and describe their meaning and reasoning. This definition is based on that used by Barosi, Magnani, and Stephanelli (1993) to describe the reasoning of physicians during diagnosis. This language often expresses the connections between evidence and hypotheses, justifications for procedures, and the tentativeness of findings. It is the language used for constructing knowledge and making firsthand accounts of that knowledge and its foundations (Anderberg, Svensson, Alvegard, & Johansson, 2008). For example, a statement such as “the carbon dioxide measurements support our initial assertion that…” expresses the researchers’ understanding of what evidence is useful (in this case, quantitative measurements of carbon dioxide concentrations), the relationship to the claim made (here the implication is specific measurements were taken to test a proposed relationship), and the degree of certainty that this type of evidence can provide (support but not confirmation, as would be typical for much scientific evidence). Epistemological language is the language of scientific conferences, journal articles, and the language spoken and written in internal communications within labs and research groups and is integral not only to communication of scientific findings but also to their construction. In describing a cognitive model of science, Izquierdo-Aymerich and Adúriz-Bravo (2003), emphasize the importance of model and theory construction to science and their inherent dependence on language: “The propositional language that defines a theory is not then used to *describe* the world but to construct a mental model of it, which is a structural analogue of the real situation” (p. 31). This statement illustrates the epistemological function of language: The language is not to describe the process but is instead itself needed to create the mental model.

In addition, the scientific community, science journalists, science teachers, and scientists themselves also engage in metalanguage—second level language used to analyse and describe the generation of scientific knowledge. This definition is drawn from the linguistic tradition and the language use of language learners (e.g., Basturkmen, Loewen, & Ellis, 2002) who not only engage is using the technical terms of a new language but also use specialized terms to communicate about what they are learning with their peers and teachers. Note that scientific metalanguage is not considered a second-level to epistemological language. It is not language about language but instead language about science. It might more properly be called metascientific language, were that term not already associated with the idea of metascientific theories (e.g., Collins, 2007). As an example of scientific metalanguage, words such as 'evidence' and 'claims' (used above to explain the quote from a research article) are not themselves necessarily part of the scientific research process but they are often used to help students and teachers analyse the work of scientists (e.g., see Klentschy, 2005, who advocates the use of these terms for helping students to frame their own scientific writing). Metalanguage is what is needed to support students in deconstructing and critiquing scientific knowledge as it is presented in scientific text. It is the language that they must understand in order to recognize and appreciate critique in others' writing about science. It is the language that helps establish what is acceptable evidence or acceptable practice and allows readers and others to discuss these aspects of science.

The word 'experiment' in particular illustrates this function of metalanguage and the difference between metalanguage and epistemological language. The word carries with it a large number of social norms (e.g., controlled variables, blind-tests, and randomization) but does not specify exactly which of these were applied in a particular situation. It is a word that allows speakers and writers to refer generally to acceptable scientific practices without describing them specifically or in detail. This allows the speaker or writer to move on to discussing, for example, the outcomes while establishing with a quick word that whatever the experimenters did was considered a scientific approach. It is a word for talking *about* science: it is metalanguage. Because of its general nature and the attached and often implicit social baggage it carries, it provides little to a scientist as a reasoning resource. One can imagine a researcher reasoning aloud saying, "Now because we controlled the temperature and air pressure carefully and changed the flow rate only incrementally, I am surprised that...", and that such reasoning may lead him or her to conceptualizing their results. One cannot, on the other hand, imagine saying that "Because we experimented with the flow rate, I am surprised that..." would provide the same resources for detailed thinking and meaning making. The word 'experiment' therefore likely has little value as an epistemological word but as metalanguage is valuable as a carrier of norms and expectations of one particular type of acceptable scientific practice. There are of course words that perform both functions depending on the context in which they are used.

Note that there is a distinction to be made here between the terms 'a metalanguage for science' and 'scientific metalanguage'. Tseitlin and Galili

(2006), for example, propose the philosophy of science as a metalanguage for science in that it provides a broad set of resources and frameworks for talking about and understanding the field of science. Their approach is concerned with the meanings generated by philosophy of science and not the language (words and sentence structures) used to actually do the work of talking about science. It is for this purpose that we use the term scientific metalanguage (i.e., in reference to the words and sentence structures).

To illustrate the importance of *both* of these types of language, one can take Bakhtin's (1986) suggestion to use implied questions as a key meaning making strategy, specifically understanding text by searching for the question(s) that it answers. With epistemological language representing (and facilitating) the reasoning of scientists and their first-hand communication of knowledge generated through this reasoning, epistemological language offers students a window to the practice of science and the ways in which those engaged in it actively work to make sense of the world. Epistemological language, I therefore propose, has the power to answer the important question: how is scientific meaning and knowledge constructed and what is the role of evidence in this process? It tells us what happens in science and how it happens. Scientific metalanguage answers the question: How is scientific evidence and knowledge enacted and judged within the culture of science? By supporting discussion and critique, giving us ways to talk about what scientists do, and making comparisons between what are viewed to be more and less robust and acceptable practices, metalanguage gives us a window to the culture of science—to what is acceptable and what is not, what is risky science and what is conventional science. It is metalanguage that represents this interplay to students and therefore offers an important opportunity to understand science as more than a set of algorithms to uncover the truth and instead as a cultural practice with norms and values. As Harrison (2005) argues:

> Students could be learning how knowledge is produced through language and power relations rather than just reproducing it for the teacher. They need to learn the skills to analyse, deconstruct and critique the ways in which knowledge is both transmitted and produced in the classroom, and they need to know what the hidden meanings are, and where they come from. (p. 876)

### *How Can Epistemological Language and Metalanguage Be Introduced and Supported in Classrooms?*

Epistemological language and scientific metalanguage exist to a certain degree in all science-focused texts that students encounter but they often exist sporadically and sometimes incorrectly or misleadingly. These issues weaken the ability for these texts to provide the important function of acting as a meaningful symbol for scientific reasoning and the culture of science. For example, consider the following excerpt from *Explore 6: A book of science* (Ingram, Herridge, & Moore, 1993) a science resource book written for the Grade 6 science program in Ontario, Canada:

> Did you ever think that there were mysterious things going on inside a glass of soda pop? Try this easy scientific experiment. Pour a can or bottle of your

> favourite soda pop into a tall glass. Now take a good look at it. Is there any action going on inside the glass? You bet. There are lots and lots of bubbles forming.
>
> Ever wondered why bubbles form in a glass of soda pop? You can't see any when the soda pop is in a sealed bottle. The bubbles are formed by carbon dioxide gas, the same gas that you breathe out. It's forced into the can or bottle when the soda pop is put in. As long as the container remains sealed, the carbon dioxide stays dissolved in the soda pop – and invisible. But as soon as you open the bottle, the gas escapes by forming bubbles. Forming bubbles is the only way the carbon dioxide can get to the top of the container (pp. 80–81).

This example illustrates epistemological language (e.g., "formed" and "forced" because they are explicit cause and effect words to describe reasoning about the bubbles) and of metalanguage (e.g., "experiment" representing and generalizing a broad range of scientific techniques). Note, however, that despite a couple of examples of epistemological language, there is very little epistemological content in this excerpt. There is, for example, little that is experimental about this experiment. As is typical in textbooks, this passage presents scientific knowledge with nearly no reasoning context (Myers, 1992). There is very little indication that people needed to use scientific reasoning to come to the explanations that are presented as fact in this passage. So while there are epistemological words, they carry with them little epistemological meaning. In addition, both are entangled with general expository language, which dominates the passage. This is a common occurrence in writing about science for children, and fleeting examples of metalanguage and epistemological language overwhelmed by general expository language will not provide adequate opportunities for students to engage with and grasp either type of language.

### *Hybrid Adapted Primary Literature*

To provide students with some of the benefits of reading scientific text that were introduced at the beginning of this chapter (e.g., understanding the rationale for research designs and procedures, exploring the important connection between chosen research methods and research questions, increasing familiarity with scientific communication and the language of science—in terms of expressions of uncertainty and appeals to authority/evidence while also making scientific writing accessible to students—researchers such as Baram-Tsabari and Yarden (2005), Falk, Brill and Yarden (2008), Norris, Macnab, Wonham, and de Vries (2009), and Phillips and Norris (2009) have proposed the use of adapted primary literature (APL). The adaptation process maintains the structure and style of the original scientific writing while adjusting for the conceptual understanding, reading level, vocabulary and mathematical skill of the students. In some instances additional background information is included and non-essential elements such as equations are omitted. The discussion is often adapted (e.g., by including further information and more explicit links between ideas) so that students can more easily make connections between the results and the conclusions drawn by the researchers. Using these approaches, APL has been shown to be effective and valuable in high school science classrooms with students developing a deeper understanding of both the content of the discipline and the processes of scientific inquiry (Baram-Tsabari & Yarden 2005; Brill, Falk, & Yarden, 2004; Brill & Yarden, 2003; Norris, Stelnicki, & de Vries, in press). APL can also provide excellent examples of an epistemological language rich resource for science teaching. For example, the following extract is from a piece of APL entitled "West Nile virus: Mathematical Modeling to Understand and Control a Disease" written by Wonham, Macnab, Norris and de Vries (2007).

> Bird-mosquito interaction
>
> The parameters associated with the dashed arrows in FIGURE 3 required a little extra consideration. In general, it *seemed reasonable* that West Nile virus transmission should *depend* on the mosquito biting *rate*, the *proportion* of bites that actually transmit the disease, and the *relative numbers* of mosquitoes and birds.

The italicized words and phrases represent examples of epistemological language. For example "seemed reasonable" illustrates that the reasoning presented here depends on first identifying plausible scenarios. The word "depend" refers specifically to dependence in a statistical sense, establishing the independent and dependent variables for the investigation. The others illustrate the type of quantitative evidence that is appropriate to this investigation: a time dependent rate and two comparative proportions. The reasoning that follows this paragraph relies on the information provided by these two types of quantities. Note that in comparison to this epistemological language, metalanguage is not dominant in this passage. There are no words or phrases that explicitly invoke or address the cultural aspects of scientific reasoning such as whether these data and this analysis approach are appropriate. Metalanguage is more prominent in secondary writing about science. For example, consider the following from *Discover Magazine*:

> This month American shad conclude their long journey from oceans to river spawning grounds. Or so conservationists hope. A four-year *assessment concluded* in 2007 that this iconic Atlantic Coast native was at its lowest abundance ever, and the decline continued last year. Shad have faced threats before. Overfishing, pollution, and the blocking of spawning grounds by dams once devastated their populations. Then, in the early 1990s, cleaner rivers, fish ladders, and fry from hatcheries spurred a recovery that looked promising. But biologists *monitoring* shad with *electrofishing surveys* (*using an electric current to briefly stun fish so they can be counted*) and *fish-passage tallies* report that the species has been on the wane again in recent years. (Cavalier, 2009, p. 15)

This time the italicized words and phrases represent examples of metalanguage. In the third sentence both the words "assessment" and "concluded" are acting as metalanguage in this passage. The word “assessment” acts as a general description of a type of research. The word following it, however, indicates the robust nature of this assessment by saying that it is strong enough to warrant conclusions as opposed, perhaps, to tentative claims. The word concluded could act as an epistemological resource for a scientist but in this case, it functions as scientific metalanguage: it allows the outside reader to understand and talk about the strength of the study without needing complete details, to gain a sense of its robustness as a result of the strength of the methods and the timeline. The word also provides information about the types of assessments that are considered firm by suggesting that whatever is described later in the passage was strong enough to warrant the word “concluded”. Later on, the word “monitored” is similarly used and it is followed by several phrases that provide more detail about what the monitoring entailed. Again this language has a metascientific function. Explaining the meaning of electrofishing has no epistemological value but it creates a shared language with the reader so that the results of the study can be understood. Along with the phrase “fish-passage tallies”, it also provides clues as to what is acceptable under the umbrella practice term of “monitoring”.

To support students in learning to use and understand both epistemological language and metalanguage, a hybrid form of scientific writing for use with elementary students is explored here. This hybrid form integrates narrative writing (which emphasizes metalanguage, as in the example above) with APL—writing that maintains the form, structure and epistemological language of a scientific journal article but is adapted to suit the conceptual understanding, reading level, vocabulary and mathematical skill of the students. This chapter explores two pieces (one for Grade 5 students and one for Grade 6) that include a narrative introduction to scientists and their research, followed by a piece of APL created from their work. The narrative writing is used to support and encourage understanding and use of metalanguage related to evidence, and the APL to introduce and encourage similar understanding of epistemological language. The written responses of three classes (two in Grade 5 and one in Grade 6) from the same school are examined for evidence of their engagement with this language.

In the context of HAPL, narrative is taken to refer to writing that is: a) action oriented (not written in passive voice), b) concrete (without widespread use of abstract noun phrases), and c) directly notes the people involved including their thoughts, motivations and actions. These are non-fiction narratives that can still be classified as informational based on their content (descriptions of scientists and scientific ideas) but because of structure of the sentences and the emphasis on people acting are best described as narratives. In focusing on the people involved, these narrative descriptions can include descriptions of motivations, challenges, upsets and disagreements, aspects that are consistent with our understanding of metalanguage as a symbol of the culture of science. The aim in teaching both of these types of language is to provide students and teachers with the opportunity to engage with the processes and meanings of scientific evidence, to have access to these two types of language as a window into the inquiry process and the culture of science.

## DEVELOPING THE HAPL RESOURCES

To explore the possibilities for this hybrid text form, two case studies were examined. The first involved a resource for Grade 6 students. It is based on an article from the journal *Geology* that describes researchers using computer-generated pictures to assess whether newly observed flow patterns on Mars are likely the result of wet or dry flow. It hinges on a model-building methodology, comparing computer-generated flow models to real world materials for the purpose of hypothesis testing. The second is written for Grade 5 students and engages in simulation-based exploration for the purposes of hypothesis generation on the topic of nano-structures. It is based on an article from *Nanotechnology Letters* and explores the possibility of using micro-droplets of water to shape graphene into useful nano-structures.

The first step in the development process of both of these resources was the selection of an example of primary literature that could be revised into HAPL, specifically one that included appropriate and accessible (or adaptable) examples of epistemological language. Using online database searches, scientific journals were searched for articles related to topics from the Grade 5 and 6 Alberta program of studies that described direct collection and analysis of data (so that epistemological ideas about evidence would be central). Review articles were not considered. Their purposes are summary and synthesis so they would not primarily exemplify the collection and interpretation of evidence. Potential candidates for adaptation were selected based on the following criteria: a) the accessible nature of the evidence, procedures and reasoning structures (e.g., qualitative comparisons of pictures or measurement of quantities familiar to students such as temperature and volume), and b) the availability of supporting materials for writing the narrative section of the HAPL (e.g., press releases, interviews and accounts of the same research from popular science sources such as *Scientific American*, *Discover*, and *National Geographic*).

## CASE STUDIES

Three classes from the same suburban Catholic school participated in using these resources (One Grade 6 class and two Grade 5 classes). The Grade 6 class consisted of 23 students and they were taught science by their homeroom teacher. The Grade 5 classes consisted of 26 and 24 students. The same teacher taught science to both groups of Grade 5 students and was also the home room teacher of one of them. As the researcher, I visited their classrooms and introduced the HAPL examples. In both grades, the students read the pieces together in pairs and worked as a group to answer discussion questions related to the nature of the evidence presented and its relationship to the respective findings. Questions were open-ended and meant to challenge students to think beyond simple reading comprehension of the text. The exact questions for each grade are presented below in the discussion of the resources. The questions are broad and do not ask about specific words. Their purpose was to explore the potential of the resources for challenging students to think about epistemological ideas related to evidence through reading and writing. The questions should illustrate the level of analysis that students engage on their own as well as places where they may need support from their teacher to make the exact connections intended in the text. These questions should also illustrate whether there are ideas about evidence not accessible to the students through these texts.

### *Grade 6 HAPL: Water on Mars? Maybe, Maybe Not*

The article chosen for the Grade 6 HAPL case study described researchers comparing photographs of newly appeared gullies on Mars to computer models of wet and dry flow to determine the most likely explanation of the gullies (Pelletier, Kolb, McEwan & Kirk, 2008). This study had also been reported in a press release from the home university of the lead researcher and had been picked up and reported by several popular science websites.

The first step in creating the HAPL example was the adaptation of the journal article from primary literature to adapted primary literature. Working section by section through the original article, sentences and paragraphs were scanned for essential information and rewritten using appropriate vocabulary for grade 6 students. Sentences were shortened and calculations, statistical analysis, scientific jargon and technical terms were removed. The overall structure of the article (e.g., the order in which the information was presented) and the grammatical style of the genre were maintained. Importantly, the overall reasoning structure (and the epistemological language that supported it) was maintained. For example, the opening paragraph in the original primary literature was:

> The bright gully sediments deposited on Mars within the past few years (Malin et al., 2006) have attracted great interest as possible signatures of liquid water flow under the present Martian climate. The distributary geometry of these deposits resembles that of debris-fan deposits on Earth, suggesting that they were transported by a mixture of sediment and liquid water. This discovery, together with that of Amazonian-aged gullies morphologically consistent with fluvial erosion (Malin and Edgett, 2000; Gilmore and Phillips, 2002; Balme et al., 2006; Heldmann et al., 2007), has challenged the prevailing notion of a dry recent Mars. Alternatively, the recent gully deposits could be the result of dry mass wasting if source-region slopes are sufficiently steep. Granular materials can exhibit fluid-like behavior (Treiman, 2003; Shinbrot et al., 2004; Bart, 2007) and hence may produce depositional landforms very similar to those created by liquid water flow. (Pelletier, et al., 2008, p. 211)

Examples of epistemological language are underlined above. These are the words and phrases that lay out the reasoning and meaning making processes that the authors are explaining. Since this is the introductory paragraph, its focus is not on the immediate data but instead on the reasoning process that brought them to conduct the inquiry that they did. For example, in the first sentence the expression "possible signatures" has an epistemological function in that it establishes that these gullies may be evidence of an underlying process and sets up the goal of the study, which is to uncover that underlying process. The gullies are set out as an effect rather than a cause or a static feature. The phrase also expresses the tentativeness of this position. The second underlined word is "present" which adds the important information that the gullies will be explored from the perspective that they are evidence of a process that is currently (or recently) underway on Mars rather than an ancient one. The next underlined word is "resembles" which sets out some of the original informal data on which the present study rests. The resemblance of these gullies to features on Earth is used as a justification for the initial hypotheses that will be laid out and explored in the study and establishes that these gullies will be explored through physical appearance (e.g., shape, depth, pattern) rather than through soil analysis, for example. Later on the word "alternatively" serves the epistemological function of establishing the hypothetico-deductive nature of the study and the basic methodology (i.e., hypothesis testing). That methodological choice is supported by the language that presents the two hypotheses (wet and dry flow). It is perhaps interesting that one hypothesis (wet flow) is already supported by evidence (the morphological similarity of specific patterns on Earth) while the other is more conjectural (granular material "can exhibit" this type of behaviour too and therefore "may produce" similar patterns). Epistemologically it is significant that they will both be considered equally in the hypothesis testing that follows because it exemplifies the examination of alternative explanations.

In the adapted version, the opening paragraph maintained these epistemological features. The words are not necessarily identical (e.g., 'morphologically consistent' is not used as it was judged to be beyond the Grade 6 reading level) but the epistemological meaning embedded in the words is the same. Note, for the sake of keeping the text as simple as possible, the in-text references have also been removed.

> The bright new marks on Mars' gullies have attracted great interest as possible evidence of recent water flow on Mars. These marks resemble marks made on Earth by mixtures of water and small grains of soil and sand. This has made some scientists suggest that the streaks could be caused by water. On the other hand, the streaks could be the result of dry particles of sand and dirt. When they move, these materials can act as though they are flowing. It is possible that dry materials could have made these streaks.

After adapting the primary literature in the manner described above, with an emphasis on maintaining and highlighting epistemological language, a narrative introduction to the study was written from the information available in the press release and popular science writing about the study. It described the context of the research, including research that had come before it, and openly discussed the reasoning processes and motivations of the scientists. Appropriate scientific metalanguage was used to be consistent with the way the study had been discussed in the secondary literature and press releases. For example, the narrative section began with the following paragraphs:

> In 2006, Michael Malin made an exciting discovery when he noticed bright new streak marks in pictures of Mars. These streaks looked like the

> marks that water leaves when it flows through sand at the beach. The streaks had not been there when the last pictures were taken in 1999. He, and other scientists, thought that they may have found evidence for recent water flow on Mars – maybe even a place where microscopic life could be found.
>
> The excitement over finding these streaks inspired another scientist, Jon Pelletier, to look at new pictures that he had just received from a satellite orbiting Mars. These pictures showed the same area of the planet in more detail than those used by Malin. He wondered if he could create a computer model of water flow on Mars and compare pictures from the model with the pictures he had of the streaks on Mars. If they looked similar, this might support Malin's explanation that the streaks were caused by the flow of water. Pelletier also thought that there might be another explanation. The streaks could have been caused by the flow of dry materials such as sand and dust. This would be similar to weathering caused by dust and dirt in the deserts on Earth. He therefore began his study with two hypotheses (the plural of hypothesis), meaning that he had two proposed explanations for the streaks.

This introduction is different from that of the APL section in the structure of the sentences (e.g., they are about direct actions by people rather than indirect passive language) and in the inclusion of information related to motivation and interests of the scientists. It is also different in the way that words are used to describe the research to be undertaken. The focus here is metalanguage rather than epistemological language. The word "discovery" is used to describe the findings of Michael Malin. Discovery is not a word that would add reasoning value for a scientist in reading this paper. It does, however, tell an outside reader that what he found was new, had not been identified before and was valuable enough to be considered a discovery. It also suggests the concrete nature of his findings in that what he reported was something that could be physically observed rather than an underlying causal relationship that he developed. The value of this finding is suggested by the later use of the word "evidence" (that the discovery could be evidence of water on Mars). This serves the metascientific function of signaling that this type of observed discovery would be strong enough to act as evidence on its own. This would be different than writing, for example, that the observation would suggest a location for searching for evidence of water on Mars. Another word of note here is that of "hypothesis." Above this was identified as a hypothetico-deductive study with an underlying methodology of hypothesis testing. That designation was made on the basis of the epistemological language used in the paper. It is important to note that the word "hypothesis" is not, however, used in the original report of the study other than in the abstract, which really serves a metascientific function rather than an epistemological one. In this case, the word "hypothesis" is an example of metalanguage that has embedded cultural understandings consistent with the specific reasoning strategies described in the original report. In using this word, the specific details need not be explicated because it carries with it the cultural meanings of hypothesis testing. Note in addition that for the purposes of using this as a teaching tool, we have included further explanation of what it means for him to have two hypotheses to test.

This is an important aspect of the purpose of HAPL—the opportunity to teach and make explicit the cultural understandings embedded in metalanguage. To further support this function, the introductory narrative was designed to guide students' thinking and encourage them to read and analyze the text in small sections. A questioning sequence was written to parallel the conceptual sequence of the metalanguage to familiarize students with the logical flow of ideas in the study before transitioning into reading the APL and its more specialized epistemological language. For example, once presented with the available evidence and before reading about what the scientists did, students were asked to predict how scientists could analyze the evidence. The narrative section went as far as describing the analysis procedures and then introduced the APL. The findings and conclusions were presented only in the APL. The APL was then followed by discussion questions designed to encourage students to identify the reasoning presented in the study and the meaning of the epistemological language in the report.

In pairs, the students were asked to discuss and then record answers to questions related to the nature of evidence in this study. They were asked two questions after reading the narrative section but before proceeding to the APL where the findings were discussed:

> Why might these streaks be evidence of recent water flow on Mars?
>
> When comparing the two pictures, which features do you think Dr. Pelletier would look for?
>
> After reading the APL section, they were asked four further questions related to evidence:
>
> After reading the report, what do you think is the main conclusion of Dr. Pelletier's study?
>
> What evidence does he have to support this conclusion?
>
> Do you think they know for sure what caused the streaks on Mars? Why do you think this?
>
> What do you think they should do next in their research? Why do you think this is what they should do?

These questions, as described above, were meant to move beyond probing their comprehension of the text and to begin to understand their engagement with the nature of evidence through the epistemological language and metalanguage embedded in the text. The first two questions completed after the APL may appear to be primarily comprehension questions but they lay the foundation for the third question which addresses the nature of evidence. These questions and the HAPL

Mars resource were pilot tested in a previous year with a different Grade 6 class. These questions were chosen as the ones most revealing of students' engagement with evidence.

*Why might these streaks be evidence of recent water flow on Mars?* As described above, this question asks students to engage with the embedded meanings regarding what is evidence and determine how the descriptions presented in the text meet this implied standard. Almost all the students were able to see physical resemblance as the standard being appealed to (e.g., "Because it looks like it was on a beach when the tide comes in, then out"; "These streaks look like the streaks on the beach"; "Because it looks like water that leaves when it flows through the sand"). These responses show a general comprehension of the opening paragraphs but also very specific understanding of the metalanguage used such as "evidence" and "resembles". These answers are written in their own words but show an understanding of the physical evidence. Some students take the reasoning a bit further and suggest other reasons why this fits with previous knowledge about Mars (and therefore might support or challenge other claims about Mars). These answers do not address the epistemological meanings of this text directly but do show a broader epistemological understanding of science (e.g., "Mars does have water but it is frozen at the two poles"). Another student took her reasoning further by conjecturing about what elements might contribute further to the resemblance, possibly taking the view that if it looks like water on a beach, it may also look like other water on Earth. In the context of this study, where visual resemblance is the key type of analysis, this conjecture is entirely appropriate: "They might be the white of ice, which is the only water that can be there".

*When comparing the two pictures, which features do you think Dr. Pelletier would look for?* This question asks all of the students to make the same type of conjecture as the last student above, probing further their understanding of the metalanguage "resemble" and the types of resemblance that would be acceptable as evidence. Neither a sense of resemblance appropriate to art criticism, such as evoking a similar emotional response nor just looking vaguely similar (as one might describe siblings) would be appropriate in this situation. The metalanguage embeds a sense of what scientific resemblance would mean. This question probes whether students engage with this meaning. Their answers suggest that it is something that these students can engage in but they do not necessarily go this deep in their thinking. Six of the students suggested very specific features that would qualify as scientific resemblance. For example, "Sand wouldn't go deep into the water at all because sand is not very heavy, so features like: Shape, Color, Size, Pattern on Surface!", "1. Same shape 2. If they were the same depth 3. Same features 4. Similar streak line". Four of the students' responses show general understanding but are too broad to make a decision about their metalanguage understanding. They write, for example, "Differences", "Whether or not the pictures look different", and "How the streaks compare to the ones on Mars". The remainder of the students answered even more generally, writing "They would look for differences" and "How the streaks compared to the ones on Mars"—answers that are not incorrect but that do not show an analysis of the metalanguage, something that could perhaps be better facilitated by the teacher or probing questions. This is perhaps a place where the text could be a valuable resource for a teacher-led discussion of the meaning of this metalanguage.

After reading the APL section, they were asked four further questions related to evidence. As described above, the first two questions probed primarily their understanding of the findings and evidence presented in the paper. The students' responses encouragingly showed a good understanding, with 19 of the students responding that dry particles most likely made the streaks on Mars. Two students (in the same pair) wrote only, "The streaks on Mars", an answer that cannot be interpreted and likely shows that they struggled to extract the meaning of the findings. Two others (another pair) left the question blank. Similarly, most of the students identified the look of the model as the primary evidence but, in line with the question above, fewer (6 students, 4 of them the same as the ones above) were specific about the exact difference between the model and the photographs (e.g., "The water didn't make 'fingers'").

*Do you think they know for sure what caused the streaks on Mars? Why do you think this?* This question, unlike the others, is directly about the nature and relationship of the evidence embedded in the epistemological language of the APL. The APL is tentative about the findings because of the model building methodology and the simplification involved. Words such as "suggest" and "possibly show" are used. Some of the students appealed specifically to challenges related to the methods (e.g., "No, because it could be mixed substance or just a plain one with only one substance like just dirt or water"—addressing a weakness identified by the authors that they had tested only pure water and purely dry sand). Most, however, reflected the general uncertainty of the findings without restating the same reasons implied in the APL. (e.g., "NO. You can never be sure what made them. It is hard unless you visit Mars and do some testing on Mars." "No, because a little more research is needed to be done. This is just the start."). Like the earlier questions these suggest that the students are prepared to engage with the idea of uncertainty in the text but need further guidance to pull out the exact meaning of epistemological language related to certainty used in this article.

*What do you think they should do next in their research?* The answers to this question are very similar and they reflect the students' epistemological commitment to concrete evidence (e.g., "I think they should take samples after they take pics because it might change if you take something out of there. I also think they should have poured a little water on the ground and look at it and see if it made that mark") but also show some acknowledgement of the specific weaknesses in this study that could be addressed (e.g., "Mix water and sand together to see if it is the same"). The combination of the text and the questions is engaging them with epistemological ideas. As above, further guidance is needed, however, for more of the students to engage with the specific epistemological language of these texts.

### *Grade 5 HAPL: Building the Smallest Things You Can Imagine*

The article chosen for the Grade 5 HAPL described researchers testing possible ways to begin thinking about a bottom up method of nano-construction (where smaller pieces are shaped and then brought together to build larger structures) as opposed to a top down method (where materials are removed from a larger piece to arrive at the intended structure). These ideas have been mostly theoretical up to this point and the researchers engaged in computer-based simulation to test the possibility of shaping nano-materials with water droplets. Like the other HAPL example, the APL section was an adapted version of the original article and the narrative section was written with reference to popular materials written about the research (e.g., sciencedaily.com and *Nanotechnology Today*). In addition, the principal investigator (and third author) provided feedback on the adaptation and additional information and included suggested explanatory metaphors for the narrative section.

This article had a very different structure from the Grade 6 case. It begins with an explanation of the various promising indications that graphene can be influenced by water, culminating in the introductory hypothesis that graphene could be shaped by microdroplets of water (the hypothesis is stated as a question):

> Carbon nanotubes (CNTs) can serve as a railroad for small water droplets. CNTs submerged in water can assemble into micro-rings around bubbles formed by ultrasonic waves. Similar assembly effects might work in 2D graphene-based systems. For example, liquid droplets can induce wrinkles on thin polymer films by strong capillary forces. Droplets can also guide folding of 3D microstructures from polymer (PDMS) sheets. The question is if nanodroplets (NDs) can activate and guide folding of graphene flakes of complex shapes, analogously like chaperones fold proteins. (p. 3766)

One structure is tested in the simulation environment (that mimics the intermolecular forces) and found to be successful. From that success various other shapes and configurations are attempted (e.g., "Intrigued by the action of NDs on graphene, we test to see if they can activate and guide folding of graphene flakes of various shapes"). Each further configuration is supported by illustrations of the resulting graphene shapes and modifications made by adjusting the temperature and droplet size. The study is exploratory rather than confirmatory and results in the generation of further hypotheses about the eventual utility of water droplets for bottom-up construction of nano-structures.

Like the Mars example, the APL section maintained the structure of the original article as well as the meaning of the embedded epistemological language. The opening section read:

> The main idea behind a "bottom-up" approach to building is to find a way to guide smaller pieces to come together to form a final product. This approach

> is easier and uses less material than a “top-down” approach where material is removed to create a final product. Guiding materials to come together when they are very small, though, is difficult. To solve this problem, we need to find ways to use other tiny particles to guide the materials to come together.
>
> One suggestion has been to use water to shape graphene. Carbon nanotubes can serve as a railroad for small water droplets. And nanotubes that are under water can shape themselves into rings around bubbles of air. The question is if tiny droplets of water (nanodroplets) can guide the shape of graphene. To answer this question, we first study the effect of nanodroplets on a graphene sheet. We study it by examining computer models that simulate the ways molecules move and interact with each other.

Here the underlined words represent examples of epistemological language. The “question” and “suggestion” here are very specifically hypothetical—not suggestions or questions in the everyday sense—and point to the reasoning that has gone into conceptualizing this paper. “Effect” here refers to direct causal interaction between two materials.

The narrative introduction, like in the Mars example, uses metalanguage to convey further information about the cultural norms and practices of science represented in the research. There is first some introductory material describing what nano-materials are, but the narrative related to the research begins with the following description:

> Petr Kral is a scientist at the University of Illinois in Chicago. In 2009, he was working on a project with two graduate students, Niladri Patra and Boyang Wang. They were very interested in using graphene to make nanostructures. Two other scientists at the University of Manchester in England had written an exciting article about graphene. They said that, like a thin sheet of paper, it could be made into almost any shape. Unfortunately, no one had yet found a reliable and easy way to do this because graphene is so thin. Petr, Niladri and Boyang wanted to see if they could find a way.
>
> To begin, they thought about lots of different ways that people can build things. One way to build a shape is to carve it out like when you make a sculpture out of soap or clay. You start with a big block of soap or clay and you can carve up and shape the block until it looks the way that you want it to. The other way to build something is to put lots of smaller pieces together. This is like building with pipe cleaners or Lego – you take lots of smaller pieces and put them together until you get what you want.
>
> Petr, Niladri and Boyang thought that graphene nanostructures might be easier to build if they thought about them more like pipe cleaners and Lego than like clay. They began to look for ways to turn graphene into the shapes they wanted. If they could make it into shapes, they could then assemble the shapes into new structures.

> One thing they wondered about was whether water could be used to mould the graphene into the shapes they wanted. Remember that graphene is so small that they cannot use any known tools to shape it. In their other research, Boyang and Petr had found that nanotubes (like the one in the picture on the first page) can act like a railroad for moving water around. They had also read that other scientists had found that nanotubes could wrap themselves around underwater bubbles to create rings. Both of these pieces of evidence suggested to them that water might be able to shape graphene.
>
> They decided to test this hypothesis. To make it easier to see and think about the graphene, they created a computer model that simulates how the water droplets will act and how the graphene will react to it. This way, they could look at it easily and try many different ways to shape it.

In the final two paragraphs, the underlined words provide some examples of the metalanguage content of the narrative. Words like "found" have embedded in them a relationship between evidence and conclusions and certainty, much like "discovery" in the Mars narrative held meanings about concrete findings. The word "hypothesis" is also used here, even though it is not used in the original article. As described earlier, the relationship between the previous research and the question proposed here suggests to the reader a procedure that can best be summarized using this word because it has embedded in it ideas about tentative and testable views proposed from prior research. This metalanguage is meant to frame the type of research for the student readers and engage them in the social language of talking about scientific work.

Again in pairs, both classes of students were asked to discuss and then record an answer to questions related to the nature of evidence in this study. They were asked two questions after reading the narrative section but before proceeding to the APL where the findings were discussed:

> Why do you think Petr, Niladri and Boyang were interested in solving this problem?
>
> Why do you think it is important that they read about the work of other scientists? (This was an important element of the justification for the study.)

After reading the APL, students responded to four questions very similar to those posed to the Grade 6 students:

> After reading their report, what do you think is the main conclusion of the research done by Petr and his students?
>
> What evidence do they have to support this conclusion?
>
> Do you think they know for sure that water can be used to turn graphene into different shapes? Why do you think this?
>
> What do you think they should do next in their research?

Because of the hypothesis generation methodology, the origins of the authors' idea for shaping the graphene is central to understanding the nature of the evidence provided here. Based on previous work they are looking for initial support for an idea about water. It is in this context that there simulation results are acceptable evidence. Getting at the nature and source of their idea was the intention behind the first two questions asked here and students responded with several appropriate answers. In response to the first they wrote: "Because it is something no one has done before", "Because no one had found the answer", "Because they wanted to see if it was possible to make shapes with graphene", and "They were interested because they wanted to challenge themselves and it is a very interesting tool". They rightly identified the curiosity and personal drive involved in studies like this rather than relying only on an impersonal view of science. One student went further and said "I would be interested too!"

Beyond just the personal nature of conceiving of scientific ideas, the second question addresses specifically the need for a framework of other results for the generation of new ideas. The text emphasized these connections and the second question was meant to probe whether students engaged with this idea that new ideas are not created in a vacuum but instead are based on a framework, often of the work of others. In response to this question, however, students relied primarily on their knowledge and experience outside of the article. Only a handful made explicit references to the way the research of others had shaped the authors' ideas. One wrote for example: "to get ideas". When you know other things that happen in a similar situation you can try to make their answer similar to yours." Instead, most wrote seemingly from their own experiences in accessing others' work and opinions: "So that other scientists can give them feedback and so they know they can make things or not make things", "So they know other scientists opinions and can help them", "So they would know how to do it right", "To see what they think and to see if they got the same thing or close or different", and "Because the evidence should match up and scientists put their ideas together". These students were accessing and using ideas related to the processes of science but did not use the text directly as a source for answering this question. This provides another place where teachers and further probing could help them discuss and negotiate the ways that prior research informs preliminary and exploratory studies like this one.

As in the Mars example, the first two questions asked after the APL addressed students' general understanding of the findings and the supporting evidence. And like the Mars example, these questions showed a generally good understanding of the study, supporting the appropriateness of the adaptation for these students. The majority wrote general conclusions such as "that graphene can bend around water" and "how graphene and water react to each other to make shapes". About a third of the students, spread across the two classes, were more specific in writing responses such as, "that you can shape graphene with different amounts and heat and water and make different shapes of graphene", and "that water can make graphene sheets roll up into different shapes like circles". Approximately a quarter of the students did encounter some difficulty either interpreting the meaning of the question or understanding the text well enough to identify the findings. They instead noted the implications of the research, the potential uses for graphene shapes that are listed at the end of the APL ("nanodevices", "They were trying to make graphene go inside people to detect cancer"). A further few students (3 in one class, 4 in the other) left this question blank.

In contrast, more students struggled to identify the evidence. This may be because this study did not have an experimental orientation and even if they understood the study the simulations may not have seemed like experimental evidence to them. There were no variables, no controls, and no comparisons. Many students left the question blank or wrote "I don't know". Others wrote the, not entirely inaccurate, response, "They just tried it" or "They tried it themselves" or similar responses such as "the experiment", "what they did", or "the results." A small number of students (4 in one class, 2 in the other) wrote more specific responses such as "the evidence is that the water bends it". In the context of exploring the value of HAPL resource, this difficulty is not seen to be crippling. The students' overall understanding of the study again points to this challenge as a potential resource—a place where HAPL might be used to challenge students and teachers to address different types of scientific evidence and investigation.

The final two questions address epistemological issues most directly. Do you think they know for sure that water can be used to turn graphene into different shapes? and What do you think they should do next in their research? Because of the technological nature of this study, the final question was not as useful as it had been in the Mars example. Students' responses were almost all in relation to things that could be built from the nano-structures and did not address the need for further investigation or evidence. A few students, however, added the insightful comments that "They should try to find a way to also prevent it from curling" and, addressing the simulation aspect that "They should try it for real" or "They should use real graphene next time". Similarly the students did not recognize the tentative nature of the findings. The overwhelming view was that the scientists do know for sure because they tried it: "They know from testing", "Yes, because they did it", and "I think that they know for sure because they tested and studied it". A few addressed the nano-scale and the simulations element: "No. Since they can't really see the graphene then they don't have proof. And doing it on the computer isn't actually real". The nature of the evidence in this case requires a more subtle discussion of certainty including the validity of simulations but also whether demonstrating something once counts as sufficient proof that it is always possible. These are nuanced views of this type of evidence though and two interpretations are possible here: that this element was too nuanced for the students or that this is yet another key articulation point where students' understanding of the nature of evidence could be expanded with the HAPL as a resource. From the cases here, this distinction cannot be made definitively and further comparative testing would be required.

## DISCUSSION

Results of these cases suggest several ways in which HAPL is a promising approach to engage students with ideas about evidence through epistemological language and metalanguage. There is evidence of students engaging with ideas about uncertainty, replication, simulation and with various types of evidence. Also evident are key sites for further probing and places where students show understanding of the research but are not yet thinking critically about the meanings embedded in the language. Their understanding can be a jumping off point for further exploration. These cases also support hybrid APL as a potentially valuable way of developing students' understanding of scientists and scientific inquiry. One of the key themes illustrated students' recognition that scientists rely on evidence and that evidence is collected and analysed in detail and often over long periods of time—examples of the type of understanding needed to answer Flick and Lederman's call for students to understand the inquiry context of the investigations that they do. For example, of the Mars study students wrote: "They had to study it. It was not a snap question where you can get it right away." The students, through reading the HAPL also recognized the work and effort that scientists put into their research and that it is difficult and time consuming work. For example, one wrote: "Scientist do many, many experiments <u>before</u> they can conclude on an answer. They also do many analyses on their evidence before presenting it". Students also recognized the scientists as people with individual curiosity and motivation. They proposed several reasons why these scientists would have wanted to conduct these studies: "Because it could have been a breakthrough in our knowledge about Mars"; "Maybe, because of [the scientist's] curiosity"; "Because it would be really interesting if there's a streak in Mars"; and "They wanted to finish the research, and find the conclusion".

The cases suggest that hybrid adapted primary literature (writing that includes both narrative and adapted primary literature and both epistemological language and metalanguage) is a promising way of engaging and supporting elementary students in reading APL and in developing their understanding of the culture and practices of science and scientists. Through the combined use of narrative and scientific genres, students and teachers may be able to further their understanding of the connections between evidence and explanation in science, the personal motivations of scientists, the importance of a framework for generating new ideas—in short, providing a place for immersion in many of the cultural practices of science.

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# 4. EXPLANATORY REASONING IN JUNIOR HIGH SCIENCE TEXTBOOKS

## INTRODUCTION

Current reforms in science education emphasize the importance of using inquiry-based teaching strategies that engage students in formulating explanations from evidence (National Research Council [NRC], 2000). Specifically, for example, the National Science Education Standards in the United States state that students in grades 5 to 8 should “develop descriptions, explanations, predictions, and models using evidence” and “think critically and logically to make the relationships between evidence and explanations” (NRC, 1996, p. 145). As an additional example, current science education curriculum documents in Alberta include outcomes that expect students to investigate, explain, interpret, and discuss evidence for scientific concepts. For example, the *Planet Earth* unit in Grade 7 includes outcomes such as “Investigate and interpret evidence that Earth’s surface undergoes both gradual and sudden change” and “Interpret models that show a layered structure for Earth’s interior; and describe, in general terms, evidence for such models” (Alberta Learning, 2003, p. 27).

Critiques of science education have suggested that science instruction often focuses on factual knowledge and on the processes of experimentation and data gathering, but deemphasizes the construction of meaning and argumentation (P. Newton, Driver, & Osborne, 1999). Furthermore, previous studies of curriculum resources—in particular laboratory activities—suggest that the activities provide students few opportunities to engage in posing questions, investigating natural phenomena, and formulating explanations from evidence (Germann, Haskins, & Auls, 1996; Tamir & Lunetta, 1981). This research seeks to determine what opportunities curricular resources provide for students to reason about explanations, where these opportunities occur, and what supports are provided for student reasoning about explanations.

## REASONING AND EXPLANATION IN CURRICULAR MATERIALS

Although teachers use a variety of sources when constructing the curriculum for their classroom, textbooks and associated curricular materials are often one of the largest drivers of curricular decisions (Woodward & Elliott, 1990). A national survey of science teachers in the U.S. found that 93% of grade 7–9 teachers used a published textbook and 45% of these teachers reported that they had students do seatwork assigned from the textbook and/or complete supplemental worksheets in

*Stephen P. Norris (Ed.), Reading for Evidence and Interpreting Visualizations in Mathematics and Science Education, 65–81.*

their most recent lesson (Weiss, 1987). Therefore, it is important to examine the ways in which textbooks and associated resources provide opportunities and support for students in regard to reasoning about explanations.

Previous studies have examined aspects of scientific reasoning and explanation in textbooks and associated curricular materials from a variety of perspectives. Studies have examined the ways textbooks engage students in scientific reasoning, including studies of themes related to scientific literacy (Chiappetta, Fillman, & Sethna, 1991; Chiappetta, Sethna, & Fillman, 1993; Lumpe & Beck, 1996), reasoning levels of textbook questions (Pizzini, Shepardson, & Abell, 1992), and aspects of inquiry in scientific laboratory manuals (Germann et al., 1996; Tamir & Lunetta, 1981). Text analyses have also examined how scientific explanations are presented in textbooks and science trade books (L.D. Newton, D.P. Newton, Blake, & Brown, 2002; Penney, Norris, Phillips, & Clark; 2003; Smolkin, McTigue, Donovan, & Coleman 2009).

Studies of how textbooks address scientific literacy provide insight into the emphasis that textbooks place on aspects of reasoning. Chiappetta et al. (1991) analyzed five science textbooks for themes related to scientific literacy. They categorized the text into four themes: (a) the knowledge of science, (b) the investigative nature of science, (c) science as a way of thinking, and (d) interaction of science, technology, and society. They found that the proportion of the textbook devoted to the investigative nature of science, in which the textbook actively stimulates thinking or doing, ranged from 1.9% to 39.4%, with the highest percentage of the textbook being devoted to the transmission of scientific knowledge. The investigative nature of science theme includes textbook material that requires students to: (a) answer questions, (b) make a calculation, (c) reason out an answer, or (d) engage in a thought experiment. Of the four themes of scientific literacy, the investigative nature of science theme is most likely to directly engage students in some sort of reasoning about scientific ideas. However, the nature of the reasoning cannot be directly determined from this analysis. Further analyses using these themes found that 22% to 46% of middle school life science textbooks and 11.6% to 36.2% of high school biology textbooks were devoted to the investigative nature of science (Chiappetta et al., 1993; Lumpe & Beck, 1996).

Even when textbooks actively engage students in answering questions, the reasoning required to answer questions is often at a fairly low cognitive level. Pizzini et al. (1992) analyzed eight middle school science textbooks and found that more than 78% of the questions in the textbooks were input level questions—questions that required students to recall information from memory or from the senses. The authors suggested that this focus on input level questions fails to develop higher order thinking skills and that questions should incorporate more opportunities for students to apply, analyze, synthesize, and evaluate information.

Science laboratory activities that are part of the textbook materials are an obvious place in the science curriculum to incorporate aspects of scientific reasoning. Tobin (1990) stated that “laboratory activities appeal as a way to learn with understanding and, at the same time, engage in a process of constructing knowledge by doing science” (p. 405). Tamir and Lunetta (1981) found that investigations in high school science laboratory manuals are often highly structured with few opportunities for students to formulate hypotheses, questions, and predictions, design investigations, and formulate new questions. Studies looking specifically at high school biology laboratory manuals found that the activities provided students opportunities to manipulate equipment and develop observational skills, though rarely engaged students in posing questions, solving problems, investigating natural phenomena, constructing answers, and making generalizations. Although the manuals often asked students to draw conclusions, they seldom asked students to provide evidence for those conclusions (Germann et al., 1996; Lumpe & Scharmann, 1991).

Examinations of the nature of scientific explanations in textbooks have also found limitations in how explanations and the discursive practices of science are presented. Penney et al. (2003) examined the textual characteristics of junior high science textbooks and found that the textbooks primarily presented facts or conclusions in an expository form. When examining the role of scientific reasoning in the textbooks, they found that on average only 5% of the textbooks involved explanations of phenomena and only 2% included reasons to support other statements. No examples of argumentative text in which ideas were supported by reasons were found.

Studies of elementary science texts have also found that the textbooks pay little attention to explanatory understanding. L.D. Newton et al. (2002) analyzed 76 primary science textbooks and found that the majority of the clauses in the textbooks were statements of fact (median of 85%) and rarely asked students for information or provided reasons for why things are the way they are. Smolkin et al. (2009) conducted a similar analysis of elementary science trade books and identified 67% of the statements as fact and description and the remainder as providing explanatory understanding.

Textbook resources often focus primarily on presentation of facts and descriptions rather than discussion of explanations and the reasons that support them. Argumentative discourse that involves discussion and justification of explanations supported by evidence is an important part of science (P. Newton et al., 1999). When scientific explanations are discussed, students often are presented with the explanations without explicit discussion of the questions that these explanations answer and "the conventional classroom seems to offer science students little, if any, opportunity to design (or even to choose) their own intentional explanations" (Gilbert, Boulter, & Rutherford, 1998, p. 10).

Previous studies have examined how textbooks and associated curricular materials engage students in aspects of scientific reasoning and how they present scientific explanations. Our study extends this work by specifically examining the ways in which textbooks engage students in reasoning about explanations. The specific questions investigated were:

- What opportunities do curricular resources provide for students to reason about scientific explanations?
- What types of explanations do the textbooks emphasize?
- How are the opportunities for students to construct explanations distributed in the various sections of the textbook materials (i.e., text, laboratories, activities, and review questions)?

## FRAMEWORK FOR EXAMINING REASONING ABOUT EXPLANATIONS

We need to begin by defining what we mean by explanations in science. What counts as an explanation and the reasoning involved in formulating explanations have been areas of discussion among philosophers of science, psychologists, and science educators for decades. In general, an explanation is an answer to the question "why?" or "how?" (Nagel, 1961; H. Simon, 2000). However, the views of what constitutes an explanation vary depending upon the purposes for examining this construct (Edgington, 1997).

Philosophers of science are interested in defining explanations in order to determine criteria for what should count as a scientific explanation. Psychologists study explanation in order to better understand the cognitive processes involved in reasoning about explanations. Science educators examine the ways that students and teachers explain scientific phenomena. Teachers use explanations to increase their students' understandings of scientific concepts, whereas students use explanations to make sense of the world around them. In this chapter we are primarily interested in this last category involving students' active sense-making of the world around them. An important part of science learning is providing students opportunities not only to understand scientific explanations, but also to actively engage in making inferences about natural phenomena in order to become independent explainers (Horwood, 1988).

So how do we define what it means to engage students in the process of explaining in science? Some cases are fairly obvious, such as when we ask students to explain why the can collapsed when water was heated in it and then it was placed in a tub of cold water. Cases such as this involve the identification of causal reasons for an event or phenomena. However, what about when we ask students to classify a rock? What if we ask students to classify a rock and provide evidence for their classification? What if we ask students to identify which of a variety of samples are the same substance and explain why? Any of these questions could provide the opportunity for students to engage in reasoning about explanations, although the specific wording, the student's interpretation, or the teacher's guidance may influence whether these questions actually result in explanatory reasoning. One thing that all of these questions have in common is that they require students to make inferences about natural phenomena. In other words, they go beyond merely describing observations or restating concepts that have been learned.

The purpose of the analysis described in this chapter was to better understand the various ways in which curricular materials provide opportunities for students to engage in reasoning about explanations. Therefore, we chose to include in our analysis all tasks that required students to make inferences about natural phenomena. Excluded from this analysis were requests for students to define, describe or explain concepts that had been previously presented in the exact same way in the text. The analysis also does not examine other scientific processes, such as asking questions, designing experiments, making calculations, creating graphs and charts, or making observations. The analytic framework we developed allows for the characterization of these tasks in regards to the various ways in which the tasks provided opportunities for students to reason about explanations.

In developing our analytic framework we drew on previous frameworks of explanation that take a broad perspective in defining the forms that explanations may take (Gilbert et al. 1988; Martin, 1972; Norris, Guilbert, Smith, Hakimelahi, & Phillips, 2005). In these frameworks, explanations may include causal, descriptive, functional, and predictive forms. In describing the nature of explanations, H. Simon (2000) distinguishes between descriptive theories that show how phenomena behave and explanatory theories that provide a causal mechanism for why they behave in that way. Although explanations are sometimes defined strictly as causal accounts, Gilbert et al. (1998) point out that descriptive explanations are often the first steps in scientific inquiry and therefore an important part of the process. We recognize that some people may define explanations more narrowly than we have here, but we believe our broader definition is appropriate in order to characterize how texts engage students in reasoning about explanations.

When conducting a text analysis, we cannot directly determine from the text the various ways that students will provide explanations. The particular reasoning that students use or the levels of specificity that they incorporate into their explanations will be determined by what they see as the purposes of the explanation and the audience for the explanation (Gilbert et al., 1998; Perkins & Grotzer, 2005). We can, however, determine from the text how students are asked to reason about explanations, including the supports that are provided for discussing aspects of evidence and reasoning.

The framework we developed for examining how textbook materials engage students in reasoning about explanations classifies the aspects of an explanatory task at three levels. The first level describes the type of explanatory process the task engages students in, the second level describes the type of explanation that a given question requests, and the third describes the ways in which students are encouraged to support and provide reasoning for their explanations. The three categories are hierarchical in that each task could be coded at all three levels, with each level a sublevel of the previous level. This framework was developed based on existing literature and categories that emerged from the initial analysis. See Figure 4.1. for a summary of the framework. We have chosen to stagger the headings in order to denote the hierarchical nature of the categories.

**Type of Explanatory Process**
Construction of explanations
Evaluation of explanations
Application of explanations

**Type of Explanation**
Descriptive explanations
Predictive explanations
Causal explanations
Functional explanations
Models

**Support for the Explanation**
Discuss evidence
Identify types of evidence
Evaluate evidence
Explain reasoning

*Figure 4.1. Summary of the framework for examining explanatory tasks in textbooks.*

### *Type of Explanatory Process*

This category acknowledges that although a large part of science involves the generation of scientific explanations, science also involves the evaluation and application of scientific explanations (Ohlsson, 1992; Thagard, 2006). Instances in which students were asked to construct explanations included being asked to generate descriptive or explanatory claims. Evaluating explanations consisted of situations in which students were provided with a claim or multiple claims and asked to determine how well the explanation or explanations fit the phenomena. Also included in this category were situations in which students were asked to evaluate their own hypotheses after conducting investigations. Applying explanations refers to what Ohlsson (1992) calls theory articulation or "the activity of applying a theory to a particular situation, to decide how, exactly, the theory should be mapped onto that situation, and to derive what the theory implies or says about that situation" (p. 182). For example in a review question students were asked, "If the 'shrinking apple' theory for mountain formation were correct, explain where you think mountains would be found on Earth's crust" (Booth et al., 2001a, p. 394). In our analysis we included instances where students were asked to apply scientific claims to particular situations, but not instances where students were asked to apply scientific ideas to design technological products.

The reasoning required to generate and choose between theories differs from that required to apply theories to particular phenomena. When generating and evaluating theories students must identify patterns in evidence, distinguish between evidence and theory, and evaluate evidence in light of possible theories. When applying theories to particular situations the theory is known and the evidence is constrained to a specific context. In the application case, the reasoning requires an articulation of how the evidence relates to the theory and which aspects of the theory can explain the evidence. Since the theory is provided, the reasoning focuses primarily on identifying the relationships between the theory and the evidence. This involves primarily deductive reasoning rather than inductive reasoning that is characteristic of generating and evaluating explanations.

### *Type of Explanation*

Explanations were identified as belonging to one of five categories: (a) descriptive, (b) predictive, (c) causal, (d) functional, and (e) models (Gilbert et al., 1998; Martin, 1972).

Examples of requests for descriptive explanations included: describe characteristics, identify relationships, identify patterns, and classify. When coding explanations in this category it was necessary to make a distinction between tasks that required students to make only observations and tasks that required students also to make generalizations based on observations. Tasks that were coded *describe characteristics* involved situations in which students were asked to summarize observations, such as, "Write a summary paragraph describing what you learned about the composition of soil in this activity" (Booth et al., 2001a, p. 389). In this case students were asked to bring together multiple observations to make a generalization about the characteristics of something. Tasks were coded *identify patterns* when students were asked to generalize relationships between a number of observations or data points and *identify relationships* when students were asked to generalize the relationship between two sets of observations.

Classification is included in the category of descriptive explanations, although the construction of explanations of this type may include both descriptive and explanatory elements (Rehder, 2003; Rehder & Kim, 2009; H. Simon, 2000). Classification involves knowledge of specific features and the causal mechanisms that link those features (Rehder, 2003). The determination of which features are relevant for category membership may be influenced by knowledge of the causal relationships between observable features (Ahn, Kim, Lassaline, & Dennis, 2000) or by causal relationships linking observable features to unobservable properties or structures (Rehder, 2003).

Predictive explanations answer the question of how a phenomenon might behave under particular conditions (Gilbert et al., 1998). Predictions may involve deductive inferences from hypotheses and generalizations, or inductive inferences based on extrapolations from patterns of past events (Gibbs & Lawson, 1992). Included in this category were tasks in which students were asked to make predictions about what might happen in the future and tasks involving retrodiction in which inferences are made about events that have happened in the past. Retrodiction is common in fields such as geology and paleontology (Govier, 2009).

Causal explanations included tasks that explicitly asked students to identify causes or effects and tasks that required causal reasoning in order to prevent effects or determine rates of change. Although students are not directly identifying the causes or effects of an event when stating how they would prevent an event from happening, by identifying the ways in which a certain outcome might be prevented students are explaining a certain form of causal relationship (Hoerl, 2009).

Determining rates of change was also included in our framework as a form of causal explanation. In order to determine rates of change, students must examine the phenomena of interest, determine the underlying causal mechanisms responsible for the change, and then infer how the causal mechanism may be influencing the change. For example, when shown a picture of a mountain with slanted rock layers or a fossilized insect in amber and asked “Do you think this change happened slowly or quickly?” (Booth et al., 2001a, p. 350), students must determine the underlying causes for the change in order to determine if the change occurred quickly or slowly.

The development of hypotheses has also been included under the category of causal explanations, because in theory these should involve the construction of possible causal explanations for an observed phenomenon (Gibbs & Lawson, 1992). However, when coding the text for situations in which students were asked to construct or evaluate hypotheses we found that the texts’ presentation of hypotheses was often problematic. What were identified as hypotheses in the texts were often predictions or in some cases not clearly identifiable as predictions or causal explanations. For example, students were asked in one lab, “How can you identify a mineral by its properties?” Students were then asked to “Develop a hypothesis based on the question above" (Booth et al., 2001a, p. 374). It is unclear in this case what sort of hypothesis the text is intending the students to develop. Student responses could describe ways that they will be able to use a mineral identification chart, which is primarily a procedural description. Alternatively they could describe the types of properties that would be useful to describe minerals, which gets at aspects of classification and the nature of the evidence used for classifying minerals. In either case, the hypothesis does not involve a discussion of causal explanations or even predictions of phenomena. We decided to include all instances where the text noted that a hypothesis was being sought. If we were able to determine the nature of the hypothesis requested, a prediction or causal explanation, then we also coded it as that type of explanation.

Functional explanations included tasks in which students were asked to make inferences about an organism's or object's function based on its structure or to make inferences about its structure based on its parts. For example, when provided with pictures of fossils, students were asked to make inferences about how the animal moved, where it lived, or how it ate (Booth et al., 2001a, p. 416). Martin (1972) and Gilbert et al. (1998) have pointed out the problematic nature of functional explanations and question whether they actually provide an explanation. However, as Martin (1972) noted, functional explanations play an important role in biology, especially in initial stages of inquiry and therefore we have included them in our framework.

Our framework also identifies tasks in which students are asked to create, evaluate or apply models. A model is a verbal, mathematical, or visual representation of a scientific structure or process (Gilbert et al., 1998; Ingham & Gilbert, 1991). For example, students were asked to draw a model of the contents of a mystery container (Booth et al., 2001a, p. 353), evaluate models of the earth's interior (Booth et al., 2001a, p. 356), and create a mathematical model to represent the relationships in a ray diagram (Edwards et al., 2001, p. 191). The construction of models involves "integrating pieces of information about the structure, function/behavior, and causal mechanism of the phenomenon, mapping from analogous systems or through induction" (Gobert & Buckley, 2000, p. 892).

### *Support for the Explanation*

This level focuses on the structural components of explanations that the text prompts students to include. Toulmin (2003) describes the structure of everyday arguments as including data, claims, warrants, backing, qualifiers, and rebuttals. The Toulmin framework has been used in science education to examine the nature of students' construction of explanations and arguments (Erduran, S. Simon, & Osborne, 2004). To examine the curricular supports for engaging in reasoning about explanations we drew on a previous framework, which breaks down explanation into three structural components based on Toulmin. These three components are (a) the claim or answer to the question, (b) the evidence used to support the claim, and (c) reasoning that provides evidentiary or explanatory support for the claim (McNeill, Lizotte, Krajcik, & Marx, 2006). These three components are used to determine how the text prompts students to support their explanations with evidence and reasoning.

We identified four different ways in which students were asked to reason about evidence: (a) discuss specific evidence for claims, (b) identify types of evidence to construct claims, (c) evaluate limitations of evidence, and (d) evaluate usefulness of evidence. In some cases students were asked to discuss specific evidence for claims and in other cases they were asked to identify types of evidence that could be used to construct claims. An example in which students were asked to identify types of evidence rather than describe specific evidence is seen in the following task: “You have been asked to join a scientific expedition to investigate a remote mountain region in the Antarctic. Your team wants to discover how these mountains formed. Describe the evidence you will look for” (Booth et al., 2001a, p. 408). In these cases, the instruction was hypothetical. There was no specific evidence that the students were reasoning about. Rather, the task required them to think about the nature of the evidence that would be appropriate to construct explanations of this type. Students were also asked to evaluate the usefulness or limitations of evidence, such as, “What physical property (or properties) did you find the most useful in classifying rocks?” (Booth et al., 2001a, p. 383) and “What uncertainties do scientists face when they investigate fossil evidence? Why do they need to investigate a variety of fossil evidence before making conclusions?” (Gue et al., 2001, p. 420). Having students evaluate the usefulness and limitations of evidence supports students in critically analyzing the relationships between evidence and claims and in better understanding the complexities of this relationship.

Our framework also identifies places in the text where students are asked to further explain reasoning for claims or conclusions. With this categorization we were interested in identifying places where students were prompted to explain connections between claims, evidence, and concepts. Coding statements of this type could not simply be done by looking for terms and explanations containing words such as ‘explain’, ‘why’, or ‘why not’, because these sometimes could be asking students to state claims, evidence, or reasoning. When coding these statements we looked at the statement in context and coded it as explain reasoning only when the text explicitly asked for some sort of claim or a specific claim was provided and then asked for further reasoning to support that claim. For example, “Which property or properties did you find the most useful for identifying minerals? Why?*”* (Booth et al., 2001a, p. 375) “Summarize the evidence you found. Does it support your prediction? Explain why or why not?*”* (Gue et al., 2001, p. 370) and “Identify each fossil type shown in the photographs on pages 418 and 419. Explain how you decided” (Gue et al., 2001, p. 422).

### *Summary*

The framework we have described characterizes how curricular materials engage students in reasoning about explanations. Text analyses using this framework can determine the content of the explanations and how students are prompted to provide explanatory and evidentiary support for their claims. This information points to opportunities that students are provided for reasoning about explanations and provides insight into the types of reasoning that students might use when formulating explanations.

## METHOD

### *Curricular Materials Selection*

Curricular materials from two junior high science programs were chosen for this analysis: *ScienceFocus 7* (Gue et al., 2001), *ScienceFocus 8* (Edwards et al., 2001), *Science in Action 7* (Booth et al., 2001a) and *Science in Action 8* (Booth et al., 2001b). These included both the textbook and associated teacher resources. The textbooks in both programs included five instructional units that contain content aligned with the Alberta Program of Studies for Science. Each unit of the textbooks included text, figures, activities, investigations, and review questions. Alongside the text of the *ScienceFocus* textbooks were small sections that provided interesting facts, science journal activities, internet research activities, vocabulary development activities, technology, mathematics, and career connections. The *Science in Action* textbooks included small sections with information on science facts, internet/library research activities, questions focused on aspects of the nature of science, and mathematics connections. The associated teacher resources included additional laboratories, reinforcement worksheets, and sample quizzes and unit tests.

In the Alberta Program of Studies, science units are designed to include a focus on the Nature of Science, Science and Technology, and on the Social and Environmental Contexts of Science and Technology. Although any of these units could engage students in reasoning about explanations, it was determined that the Nature of Science units would most likely contain these sorts of activities. The Nature of Science units emphasize the role of observation, evidence, interpreting, predicting, and explaining in science as evident in the statement regarding the Nature of Science in the Alberta Program of Studies for Science, grades 7-8-9:

> Science provides an ordered way of learning about the nature of things, based on observation and evidence. Through science, we explore our environment, gather knowledge and develop ideas that help us interpret and explain what we see. Scientific activity provides a conceptual and theoretical base that is used in predicting, interpreting and explaining natural and technological phenomena. Science is driven by a combination of specific knowledge, theory and experimentation. Science-based ideas are continually being tested, modified and improved as new knowledge and explanations supersede existing knowledge and explanations. (Alberta Learning, 2003, p. 4)

Due to this emphasis, we decided to focus our analysis on these units, which resulted in the selection of one unit from each grade level: *Planet Earth* for grade 7 and *Light and Optical Systems* for grade 8.

### *Text Analysis*

In order to examine all components of the textbook and associated curricular materials, it was necessary to choose a unit of analysis that could be applied to text, figures, activities, investigations, and review sections. Our unit of analysis was therefore defined as an *explanatory task*. An explanatory task was defined as any exercise that involved the generation, evaluation, or application of descriptive or explanatory claims, or tasks that engaged students in reasoning about the evidence for claims. Explanatory tasks could consist of: (a) a section of text or figure that asks students questions, (b) an activity, (c) a laboratory, or (d) a review question.

Tasks in which the answers to the questions were directly provided in the text were not included in this analysis. At the start of the chapter the text sometimes asked rhetorical questions that were then immediately answered or the text pointed out when in the chapter the question would be answered. Review questions sometimes appeared to require students to construct claims based on what they had learned, but a search of the text showed that the answer was provided and only required students to find that answer. Neither type of task was included.

The texts were coded by two raters working independently. Ratings were then compared and, in cases where there were differences in coding, each case was discussed until agreement was reached.

## FINDINGS AND DISCUSSION

In this section we first examine how the texts engaged students in constructing, evaluating, or applying explanations and how these opportunities for reasoning about explanations were distributed among the text sections. We then examine the types of explanations that the texts engaged students in constructing. Lastly, we discuss the supports that the texts included for students to provide evidence and reasoning for explanations.

### *Type of Explanatory Process*

In both the *Planet Earth* and the *Light and Optical Systems* units students were more frequently asked to construct explanations than to apply or evaluate. This finding is not surprising, because constructing explanations is an important part of science and science learning. However, there was limited inclusion of opportunities for evaluating and applying claims showing that the texts are missing opportunities for the students to engage in these important aspects of reasoning about explanations. As has been argued by others, applying and evaluating claims are important components of science (Ohlsson, 1992; Thagard, 2006). Evaluating and applying claims also engages students in critically analyzing explanations in ways that may or may not occur when explanations are constructed.

Both textbooks and both units were found to provide students the possibility to engage in reasoning about explanations. The textbooks integrated opportunities for reasoning about explanations in the review questions and the text sections, as well as in the laboratories and mini-activities. Although we cannot directly compare the number of instances of explanatory tasks in laboratories to text sections we can compare the way the explanatory tasks were distributed among different sections. In the *Light and Optical Systems* unit, the explanatory tasks were distributed similarly among section types in both *ScienceFocus* and *Science in Action*. However, in the *Planet Earth* unit, *ScienceFocus* was more likely to engage students in constructing claims during laboratory activities than in any other areas of the text, whereas *Science in Action* was more likely to incorporate reasoning about explanations throughout the textbook and associated curricular materials. In addition, the evaluation of claims in the *ScienceFocus Planet Earth* unit occurred only in the labs, whereas *Science in Action* included opportunities to evaluate claims in the mini-activities and review questions as well.

The integration of reasoning about explanations throughout the text is more likely to encourage teachers and students to see this as an integral part of science and science learning, rather than something to be done only during labs. However, it should be noted that the use of explanatory tasks is dependent on specific teacher approaches. For example, students' engagement with the explanatory tasks embedded in the text will depend upon whether the reading is assigned for independent work or is used interactively with the students. The opportunities that were embedded in the text allow students to reason about explanations as they are reading about new concepts and ideas. This supports their meaning making of the ideas and allows students to consider how the ideas apply to other situations and their own lives. However, if textbook reading is assigned as independent work, then students may not take advantage of these opportunities. Many of the explanatory tasks that are embedded in the text were included in the figures and supplementary information set in the margins that accompanied the text. When engaged in independent reading, students often ignore the figures and supplementary material that is separated from the main text (Weidenmann, 1989).

### *Types of Explanations*

In both the *Planet Earth* and *Light and Optical Systems* units students were engaged in constructing a variety of types of claims, including descriptive, predictive, causal, functional, and model-based claims. The *Planet Earth* unit included a few types of claims that were not present in the *Light and Optical Systems* unit, such as retrodiction, preventing effects, determining rates of change, and inferring structure from parts. These types of claims are specific to the geological content in the *Planet Earth* unit. Even though the current analysis examined only units from two different content areas, this analysis does show that there are likely to be differences in the types of claims and in the nature of the reasoning required to construct different types of claims. For example, as described earlier, determining rates of change requires examining the situation, considering causal factors influencing the changes that are occurring, and then inferring how those causal factors may be influencing rates of change. This combination of descriptive and causal reasoning differs from explanatory tasks that ask students only to directly identify causes or effects, which were more common in the *Light and Optical Systems* unit.

When examining the types of claims that students were asked to evaluate we found that the texts engaged students in evaluating theories and models, specific claims stated by the text or other students, and their own hypotheses and predictions. However, the two texts differed in the emphasis placed on the types of claims that were evaluated. *ScienceFocus* was more likely to engage students in evaluating their own predictions and hypotheses than *Science in Action*. *Science in Action* was more likely to engage students in evaluating a variety of types of claims, including their own hypotheses, scientific theories, and models.

### *Support for the Explanation*

Students were asked to construct claims much more often than they were asked to discuss the nature of evidence or explain their reasoning. Students were often asked to construct, evaluate, or apply claims without specific requests to support those claims with evidence or reasoning. It is possible that students would include aspects of evidence and reasoning in their explanations, but our analysis shows that the textbook materials rarely explicitly ask for these important components of explanations. Teachers could incorporate these supports into classroom discussion and supplementary materials, but without the detailed supports being present in the text, this puts more responsibility on the teacher to provide this support.

Even though the explicit requests for students to discuss aspects of evidence and reasoning were limited in the text materials, overall the texts asked students in a variety of ways to reason about evidence. Students were most commonly asked to discuss evidence for claims, and in a few instances students were asked to evaluate the value and limitations of evidence, and to identify types of evidence that would be needed to support claims.

Comparison of the texts shows differences in the level to which they included these opportunities. The *ScienceFocus* text was the only one that engaged students in explicitly discussing the limitations of evidence. This is an important part of understanding the relationship between evidence and explanation and is interesting that this is entirely missing from one of the texts.

The *Planet Earth* unit asked students in a wider variety of ways to reason about evidence than the *Light and Optical Systems* unit. This was evident in regards to supports for providing evidence and reasoning. In the *Light and Optical Systems* unit there was only one instance in which students were asked to identify types of evidence, one instance where students were asked to evaluate the usefulness of evidence, and nowhere in the unit in either text were students asked to evaluate limitations of evidence. The difference between these two units might suggest to students that the nature of the explanations in the *Light and Optical Systems* unit are more straightforward and less consideration is needed of the evidence that supports the ideas in this unit. These differences between content areas need to be examined in more depth in future studies. Engaging students in examining the nature of evidence and supporting their explanations with reasoning is important in order to support students in better understanding the relationships between evidence and explanations.

## CONCLUSIONS AND IMPLICATIONS

Our primary goals were to identify the nature of the opportunities and supports for reasoning about explanations in current science textbook materials. In order to do this we developed a framework for examining the various ways that texts might engage students in reasoning about explanations and the supports for students to provide evidence and reasoning for explanations.

The results of the analysis of two units from two different publishers suggest that the texts provide multiple opportunities for students to engage in the construction of explanations, and more limited opportunities for students to evaluate and apply explanations. There is a need for increased opportunities for students to engage in the application and evaluation of scientific explanations. Through such opportunities, students will more likely develop the skills needed in negotiating competing scientific claims, as well as in discerning the connections between and among claims, evidence, and reasoning.

Our analysis also found that the texts provide limited prompts for students to support their explanations with evidence and reasoning. Previous studies have found that students often use inadequate evidence to support their claims (Jiménez-Aleixandre, Rodríguez, & Duschl, 2000; Sandoval, 2003; Watson, Swain, & McRobbie, 2004) and that providing explicit supports can improve the quality of students' explanations (Sandoval & Millwood, 2005). Textbook materials are an important place to provide these supports.

By becoming more aware of the opportunities that already exist in the textbook materials for reasoning about explanations, teachers could further capitalize on these affordances. Teachers could build on the current curriculum by utilizing the prompts that already exist in the textbook materials for constructing explanations and, where aspects of reasoning about explanations are omitted or inadequate, provide additional supports to encourage students to further discuss the evidence and reasoning for their explanations.

Our framework for examining the nature of explanations could also be used by curriculum designers to examine the opportunities for reasoning about explanations within curriculum materials and to diversify these reasoning experiences.

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# 5. THE ENVIRONMENT AS TEXT: READING BIG LAKE

## INTRODUCTION

The study of the natural environment has a history as old as science itself. It was through early people's natural curiosity of the environment that science emerged and developed. Today, the study of the natural environment continues to have a strong focus in science as we try to understand and predict the impacts of the many environmental challenges caused by an ever-expanding world population. As a scientific research tool as well as a science education pedagogy, the study of the natural environment is an inquiry undertaken by both scientists and educators, albeit with the different objectives—generation of new knowledge or the teaching of that knowledge, respectively. Regardless of the type of inquiry, there is increasing evidence of the benefits of studying the natural environment, such as nature as therapy (e.g., Wells & Evans, 2003). There are also affective benefits when individuals recognize themselves as part of nature and thus begin to value, cherish, and protect the natural world (e.g., Kals, Schumacher, & Montada, 1999).

This chapter explores how scientists and educators view a wetlands natural environment in the context of the development of site-specific science education resources for use in high school biology teaching. We use the notion that the natural environment is a social construct that can be read, and draw upon the significance of this construct to help students and teachers appreciate and value the complexity of ecosystems.

A wetland is a highly complex ecosystem in which organisms are so interconnected with each other and the environment that it is often very difficult to distinguish the contributions of different species in it. Moreover, many organisms are not visible, either because the untrained eye cannot see them or because their life habits mean they are not evident when an observer is present, such as commonly happens when a class of 30 high school students descend! However, each and every organism in that ecosystem will have played a role in shaping the physical and biological environment.

The wetland ecosystem explored in this chapter is Big Lake, which is part of Lois Hole Provincial Park on the Sturgeon River Watershed near Edmonton, Alberta, Canada. It covers an area of 11.2 km$^2$ as part of the larger Sturgeon River Watershed, which lies within the Central Aspen Parkland ecoregion of the province between the Boreal Forest to the North and the Grasslands to the South (Alberta Community Development, 2002). As the name suggests, Big Lake has a large surface area and at its widest points is about 3 km wide and 8 km long

*Stephen P. Norris (Ed.), Reading for Evidence and Interpreting Visualizations in Mathematics and Science Education, 83–100.*

(Horstman, 2006). As a typical prairie lake, it is very shallow, nutrient rich and highly productive (Alberta Lake Management Society, 2006). Lois Hole Provincial Park is a significant staging and nesting area for many waterfowl and shorebirds and is home to over 235 species of birds (Elliot, Nelson, & Constable, 2004) in addition to a variety of mammals, amphibians, reptiles, and fish. As such, the area has been promoted for its diversity and abundance of species and wildlife habitats, which range from lake, marshland and riparian habitats, to upland coniferous and deciduous forests that contain highly diverse vegetation with unusual and rare plant species including orchids, ferns, and mosses (Vitt, Marsh, & Bovey, 1988).

Not only is the area of importance due to its significant natural history, but it has a rich human history as well. Archaeological studies have identified sites of cultural significance along the shores of the lake that have been found to contain stone tools, arrowheads, and other artifacts, which attests to the importance of the area to Prehistoric people in addition to the historical use of the area for Aboriginals and early Europeans (Baldwin & Hansen, 1978).

In 1999, the Alberta Government created the Lois Hole Provincial Park and declared it a “Special Places 2000” site. In 2001, it was given the status of a globally significant Important Bird Area (IBA) and is included in the province’s “Wetlands for Tomorrow” program in recognition of its status as one of Alberta’s most important waterfowl habitats by Ducks Unlimited (Canada) and Alberta’s Fish and Wildlife Division. The Big Lake Environmental Support Society (BLESS) was named the official volunteer steward of the natural area in 2002 and was an integral player in the designation process as a provincial park and is committed to the conservation of the Big Lake wetlands, through advocacy, public education, and stewardship.

Due to its shallow depth and eutrophic nature, the lake is not suitable for traditional water-based activities (Horstman, 2006), yet “there is a high potential for passive recreational activities including walking/hiking, bird watching, nature photography, and environmental education” (Alberta Community Development, 2002, p.59). The Big Lake Natural Area Management Plan (Alberta Community Development, 2002) recognizes the importance of the area for outdoor recreation, ecotourism, natural heritage appreciation, and environmental education and interpretation. The area has the “potential to become a nationally-renowned nature reserve” (Alberta Community Development, 2002, p.69). The plan further advocates for the establishment of public stewardship initiatives, conservation, research, and monitoring programs that could help to establish a baseline of information to monitor and evaluate the biological health of the Big Lake Lois Hole Provincial Park (Alberta Community Development, 2002).

The Canadian Wildlife Service has reported that “in all of western Canada, no city or centre of population has such a potential beauty spot on its doorstep” (Surrendi, 1969). The Big Lake Natural Area Management Plan (Alberta Community Development, 2002) recognized the importance of the area by stating that “with careful planning, in future, BLNA can become the symbol and focus of coordinated environmental protection efforts that extend well beyond the immediate boundaries of BLNA, and will serve as a biological indicator for the ecological 'state of health' of the region as a whole" (p. 69).

The ecosystem of Big Lake is full of information and communicative relationships, and is a place where many participants (non-human and human) have contributed to the structure, processes, and management that make it such a unique and important habitat—from beavers constructing their lodges and dams to humans constructing boardwalks, from algae in the water to interpretive signs for the public. The notion that the environment is socially constructed has led a number of authors to consider nature as text and the environment as something that can be read (e.g., Bishop, Reid, Stables, Lencastre, & Stoer, 2000; Maran, 2007; Stables 1996, 1997, 1998). Stables (1997), who has written extensively in this area, suggests that in landscapes the network of shared meanings extends beyond the human sphere and that it is difficult to make a distinction between the creative activities of humans, other life forms, and natural forces. As such, nature becomes a medium or interface, which different living beings read and where they write (Maran 2007). So the beaver is just as much an author as the scientist's research account of its behaviour. The tracks of wild animals in the landscape, which connect drinking places, feeding areas, and resting places, are part of environmental script (Maran, 2007). Although the descriptions of such changes in the environment and the names of animals that have caused these are attributed by human culture, the ant nests and beaver dams in themselves are the creation and self-expression of animal authors (Maran, 2007). From such a viewpoint, the natural environment can be understood to be a result of common creative activity, written by individuals of many different species, each proceeding from their own sign system and life activities (Maran, 2007). The network of shared meanings that created, and represents, the landscape therefore goes beyond the human. Stables is inspired by the work of Saussure (1959), who regards signs or symbols that signify meaning as things that can be read (Stables & Bishop, 2001). Stables (1996) states, "we 'read' the environment as part of a complex process of generating and responding to texts. Our responses to environment form an element in the network of shared meanings which embodies society" (p. 192). The concept of environment as text is also expressed in the writing of Golley (1998), who regards landscape to be "a text that informs us about its capacity to produce and support life, its history, and what organisms are likely to be present" (p. ix).

Moreover, Gadamer states, "That which can be understood is language" (1975, p. 475). When we conceive of the physical world as environment, we are responding to it, and perhaps remaking it, very much in terms of a cultural artifact (Stables, 1996). Baynham (2001) further builds on these notions when he explores how rural Australians read the weather. Chambers (2007) indicates that in addition to authors who are explicit about environment as text, there are those who treat the idea implicitly within their works, particularly in terms of our interrelationship with nature, environment, or Earth (e.g., Abram, 1996; Kahn, 1999; Orr, 1992). One of the challenges of reading the natural environment as text is that information is not presented linearly as it is normally presented in written text, and thus a more useful parallel might be to draw on visual literacy or the interpretation of images.

The adage ‘A picture is worth a thousand words’ refers to the idea that a complex idea can be conveyed with just a single still image. Further exploration of reading images is considered through the social semiotic perspective of Kress and van Leeuwen (1996) and the work of Moss (1993), who explores children watching television in terms of reading practices. The photograph of Big Lake in Figure 5.1 represents a myriad of parallel events and stories with various media and sign systems equivalent to text constructed from different languages and cultures. Thus the natural environment is similar to foreign cultural texts, which are imported or carried over from another culture, or to historical texts, which have been long forgotten and then retrieved (Maran, 2007).

Our interaction with the environment is thus one of semiotic engagement. To be environmentally literate is to be able to interpret the signs in our environments (often, but not exclusively, visual) at a number of levels. Such interpretation is largely undertaken through spoken and written language (Soper, 1995). If the nature experience of the reader is very different from that of the author or is absent altogether, then many meaning connections remain inaccessible to the reader. It thus makes it difficult for outsiders to read and understand the text and is one reason why many teachers feel ill-equipped to take student groups outdoors—the text is possibly difficult to decipher. Val Plumwood (2002) regarded society’s lack of connection with the natural world as not a symptom of the environmental crisis but as *the* environment crisis and explains why there is negligence and lack of knowledge about nature’s forms of being, various signs, and communication processes within it. Given the complexity of environmental text, it is no wonder there might be different ways to interpret and read it. In this chapter we present how scientists and educators read Big Lake when collaborating on developing site-specific education resources.

*Figure 5.1. Big Lake (Photo: Dave Conlin).*

## SCIENTIFIC, ECOLOGICAL, AND ENVIRONMENTAL LITERACY

The use of the word 'literacy' traditionally refers to text. For example, Wikipedia defines it as: 'the ability to read for knowledge, write coherently and think critically about printed material" (Wikipedia, 2011). However, we now see literacy taking many forms, some which are not related to text at all, for example, visual literacy, and some of these literacies are explored elsewhere in this book. The types of literacies specifically relevant to our work here are scientific literacy, environmental literacy, and ecological literacy and there are many definitions and interpretations of each. Interpretations of ecological and environmental literacy rarely connect to the notion of environment as text but focus more on the scientific ecology.

Orr (1992) was one of the first to use the term ecological literacy and considers it to be the ability to understand the natural systems that make life on earth possible. He believes it to be "driven by the essence of wonder, the sheer delight in being alive in a beautiful, mysterious, bountiful world" (p. 86). Ecological literacy thus implies a basic understanding of the natural world and the interconnectedness of life, which itself is built on understanding fundamental scientific principles. Moreover, ecological literacy also implies an ethic of care and stewardship where there is "practical competence to act on the basis of knowledge and feeling" (Orr, 1992, p. 92).

Capra (1996) defines being ecologically literate as "understanding the principles of organization of ecological communities (ecosystems) and using those principles for creating sustainable human communities" (p. 297). His definition is framed within systems thinking and focuses mainly on the science, such as on the interconnection and complex relationships within ecosystems—interdependence, partnership, recycling, flexibility, diversity, etc. The provision of scientific facts about the functioning of ecosystems will not necessarily achieve the sense of awe, wonder, stewardship, or engage individuals in pro-environmental behaviours. In fact, there is a well recognized gap between provision of scientific knowledge and pro-environmental behaviour (Scott, 2002). Chambers (2007) suggests that the textual / literacy notions of reading and writing equate to responding to and acting on the environment, and thus taking action is inherent within the concepts of ecological literacy and environment as text (Stables & Bishop 2001).

Environmental literacy tends to be viewed a little more broadly than ecological literacy, although the terms are often used interchangeably. The Environmental Literacy Council (2002) considers environmental literacy to require a fundamental understanding of the systems of the natural world, the relationships and interactions between the living and non-living environment, and the ability to deal sensibly with the problems that involve scientific evidence, uncertainty, and economic, aesthetic, and ethical considerations. Schneider, however, believes that it is "an unattainable goal to expect students to gain a detailed knowledge about the content of all environmentally relevant disciplines" (Schneider, 1997 p. 457). Instead, he proposes that for environmental literacy, students should be taught how to ask three questions of the experts: What can happen? What are the odds? and How do you know? (Schneider, 1997, p. 457).

A more generic analysis of literacy is considered by Stables, (1998) who argues for a tripartite division of literacy skills as functional, cultural, and critical, and indicates that this can be useful in both planning and evaluating environmental education initiatives. He describes functional environmental literacy for example as being able to recognize, remember, and name components and systems of the environment, which in Big Lake might be identifying an Osprey or beaver lodge. This would not necessarily be just relying on memory but may involve some deduction based on known properties or similarities with other habitats or organisms that might have been studied. It thus requires a scientific understanding of foundational ecological concepts related to land-water systems, ecosystems, and populations and communities (Capra, 1996). Functional environmental literacy is exemplified in traditional fieldwork activities as part of school science education. Students armed with clipboards wander about natural habitats and check off observations of plants and animals, and possibly animal tracks and scat, or count seemingly endless numbers of individual plants in quadrant samples. This type of literacy rarely elicits deeper understanding and, although it often makes for a fun day out, misses opportunities for socially responsive education. "Functionality without cultural sensitivity and critical reflection is potentially as destructive as constructive, even if it is a functionality that takes some account of, say, resource management and social and environmental consequence" (Stables, 2001, p. 252). Knowing the names of organisms at Big Lake does not necessarily guarantee environmentally responsible behaviour—for that to occur, values and a sense of connection and place are essential and thus cultural and critical literacies must form part of any educational experience provided there.

The creation of educational partnerships exemplifies the trend towards a social-constructivist view of learning. According to this view, an individual's knowledge of the world is constructed through social interaction, and the constructed knowledge is negotiated and shared with other members in a social context (Vygotsky, 1978). There is an understanding that knowledge is not held by just one of the stakeholders, rather it is socially constructed through collaboration with all the research partners and participants. The lens of social constructivism also alludes to the relevance of place-based education and biological fieldwork in providing students with opportunities to connect with themselves, their community, and their local environment through hands-on, real-world learning experiences. In the research described in this chapter, a collaboration between scientists and educators in the development of educational resources was further facilitated by engaging a group of conservationists and experts within the community and these reflect the diverse disciplines and perspectives needed to address the local ecology, relevant science, and environmental issues of Big Lake. The voices of the scientists and educators are used in the next few sections to help describe their reading of Big Lake.

## HELPING STUDENTS READ THE ENVIRONMENT

The goal of this study was to develop teaching resources to help teachers provide effective and meaningful educational experiences specifically at the Big Lake wetland ecosystem. There are general resources available to help teachers in the teaching of aquatic ecosystems, but for many teachers there is a need to have certainty about a specific site being visited. This desire for certainty is one reason why some teachers hand over such experiences to other educators such as parks staff, field center tutors, etc. (Barker, Slingsby, & Tilling, 2002). Teacher confidence about doing fieldwork with students is certainly a barrier to taking students outdoors (Braund & Reiss, 2006). Even teachers in our research who were advocates of outdoor science teaching suggested that a lack of confidence and of knowledge hindered their fieldwork teaching with students. One teacher commented, "It's totally embarrassing for a biology teacher, but my kids were like, 'You're a biology teacher, you should know that'".

It is likely that teachers with more generalist training in the sciences, or who are teaching out of their field of expertise, may feel less confident about teaching ecology and, as a result, avoid or rush fieldwork (Lock, 1998). Likewise, teachers often have particular methods that they are comfortable using in the classroom and do not feel comfortable diverging from this repertoire of practice (DeBoer, 2000). The high school science teachers who participated in this study indicated that, to be able to read Big Lake, one needed at a minimum to be able to recognize and name species. This view explains their focus on functional environmental literacy. For some teachers, this seemed to be such an overwhelming task that they believed they needed specialist scientific support to help them.

> I think some teachers need experts in the field. I mean, no invertebrate zoologist knows everything an Alberta botanist knows. They don't, right? So how can you be jack-of-all-trades as a classroom teacher? You just can't! (Teacher)

A comment such as above endorses the views of Schneider (1997) that students can't be expected to know everything in the environmental sciences but that we should concentrate on aspects of critical literacies. Nevertheless, scientists and teachers emphasized functional ecological literacy through the need to know names of species:

> Where I am from, we have 5 times as many plants as in Alberta. Our teacher said, 'You're going to have to learn something like 2000 plant names. If you don't like it, I don't want to hear about it. Just suck it up and do it because it will be with you for the rest of your lives, and you'll go to new areas and be able to extend it. So, you should be able to identify anything, at least to the genera level, and maybe the family level.' So he was saying, just suck it up – not real motivating. But you can't study ecosystems without knowing the

> elements. You have to know what you are dealing with...there is no way of getting around it, you need to know the plants, or a good portion of them. (Scientist)

Unfortunately, the large amount of facts that are known is precisely the kind of barrier that might serve to discourage teachers from doing fieldwork. On the other hand, if the focus was not on memorization, which does little to motivate students, but rather on getting to know their local natural area, perhaps the focus on details would be easier to accept.

> Personally, I think anyone who is not formally trained as a biologist benefits from knowing the species, or something about them, at least a good chunk of them. Starting with broad concepts, like energy flow, or the water cycle, that is not intrinsically nifty...but something with a face is nifty, like a flower. Once you have some idea of what is living there, then you can start connecting those pieces and looking for broader ideas. So I think just getting to know (like Robert Batemen's latest theme), getting to know what is out there. We need kids who can recognize as many birds and mammals as they do Pokeman critters...that is important. And then you can start building on more theoretical ideas and abstractions. (Scientist)

Such discrepancies in how to read Big Lake indicates the importance of dialogue between scientist and educator stakeholders. Needed for the resources is identification and agreement upon the central ideas and key concepts relevant to the natural area. Then we need to integrate these necessary elements into educational materials that maintain links to the curriculum guidelines. As a way of attending to these needs, an appropriate integration approach would have to ensure that the addition of disciplinary knowledge is logical and justified within the demands of the curriculum and the specific themes developed for the natural area resource. Likewise, the knowledge acquired from the experts of each scientific discipline needs to be condensed and simplified for translation into an age-appropriate and locally relevant educational resource. There was a general understanding and acknowledgement by scientists that any program developed, along with related resources, would need to be targeted to specific curriculum areas and that this was where teacher expertise was valuable.

## READING THROUGH INQUIRY

How to access the environment as text is a critical issue, because simply expecting students to have the skills to read an aquatic ecosystem is unrealistic. For most students, an organized school trip to Big Lake most likely would be their first visit there. So how do we start? Both the educators and scientists advocated for using inquiry-based reading, with a focus on constructing knowledge through experiential, outdoor learning activities.

> What students learn about the environment is greatly influenced by how they are taught. When we investigate the environment with reference to the

> Sturgeon River Watershed, it is difficult to involve participation of students in environmental stewardship unless they are actively engaged in a context that is relevant to them. This is impossible to do unless we actually are in the natural outdoor world. (Teacher)
>
> You need to give them permission to get muddy and get in there and do stuff…and all of a sudden they are all over it. I mean, you've got them...the hook is set. And the questions will start coming, and they will start chasing frogs and tadpoles, and it snowballs from there…So they have a task...they have something they have to accomplish. That's the problem-solving bit and they have to do some reading on it, and prepare for it. Whatever they have to do before they go out there—they can do a frog-call survey, a point count for birds, or something like that—they need to do the preparation. Then they execute the task…It will be fun, its experiential, hands-on. Then they come back, analyze, do the write-up, and reflect on it. That's the formula I would use. (Scientist)
>
> I think that's the single most important place to have hands-on things—wetlands...to get them excited…You need to build the love, to demystify the fears. There is so much stuff going on out there, from the invertebrate community, the sounds, the smells. And water is a natural magnet. I think that should be the focus, definitely, fun and fear reduction. And less cognitive, more experiential. (Scientist)
>
> It's the actual experience of it...the desire for the real environment…it affects you differently. You can smell things, and you feel things in a different way. And you touch things in a different way than you would just seeing them. Visual is fine, and even reading about them or hearing someone speak about them. All of that is valuable too. But it is not the same as actually watching birds fly overhead or from one tree to another. Or bugs flying around. Or smelling flowers or seeing stuff growing. It just isn't the same experience. (Teacher)

Whilst all these viewpoints imply an inquiry approach, there were significant differences in how inquiry was articulated, with few (both scientists and educators) using language that is commensurate with current models of science inquiry for instructional purposes (Anderson, 2002). A key missing strategy is to get students to ask questions about the environment, because this is an important starting part of any inquiry model. To ask a question implies observation of interesting environmental phenomena that might be worthy of further investigation: Why is there more lichen growing on this tree species than on that tree species? Barker and Slingsby (2011, p. 254) suggest the following strategies to help students develop a more systematic approach to observation, prediction and hypothesis formation:

- be curious
- notice interesting patterns
- describe patterns more carefully
- formulate hypotheses

- make predictions
- test ideas.

## READING FOR RELEVANCE

How relevant is Big Lake to the students? How important is relevance in the development of the teaching resources? Teachers rated relevance quite highly:

> I have actually asked [the students]...which parts did you enjoy, why didn't you like this. So they say that's boring, this is boring, or not boring, I'm not interested in that. And then, I have said 'Well, did you like to go out in the field? 'Oh ya that was fun!' Okay, so if you like to go out into the field, but you didn't want to learn about trophic levels, and you didn't want to learn about abiotic factors, but you like to go out into the field...how can I get to the things they like to do, without...all the other stuff? There has got to be a way that I can change the way I deliver the program to tap into at least what they are interested in. Let's just face it: when you are teaching there are just some days that are going to be a dog day. And yes, I'm sorry, but you've just got to do this, we've got to learn this part, you have to learn this theory, you've just got to get this information. But how can you change it so that it's more relevant to them? (Teacher)

> The challenge I guess is just how to make it meaningful, right? [There are] all kinds of ways we could do that. But, when it actually comes to doing it in class, sometimes, it's that hook, it's that newspaper article. How do you get the kids to actually care? And sometimes it is as stupid as 'Hey, you are going to get a day off school. Let's just go and be outside for a day'. Right, and then maybe, they kind of care about it a little more. (Teacher)

Teachers are acutely aware of management issues that ensue when students are not motivated and engaged. Thus, relevance and motivation were often discussed by them. Scientists were less aware of this necessity and implied that the intrinsic interest of the site would be enough to engage students. Scientists also implied that perhaps the fun element of fieldwork detracts from the science and that teachers should do more follow-up with the students.

> I have noticed when students have come back from field trips...they would talk about the good time they had but they never mention the curriculum or the subject matter [they] are studying. Why? Because they had such a good time! And I think the way we failed is that we didn't have a display board put up in the school…We didn't put up the displays of what was actually accomplished on the trip. And so, if the displays were put up in the hallways, and it was this class and that crazy [teacher] who took us out and showed us all this stuff, and then you would have others...Even the principal would walk by and see it. The teachers would walk by and see it, and the kids are talking about the good time they had. But a lot of other kids who didn't talk to the kids would see the displays. And I think we didn't do that enough. We didn't promote what we were doing as much as we should have. (Scientist)

## READING FOR PLEASURE

Both scientists and educators considered the aesthetics and awe and wonder of Big Lake to be just as important to students as the science.

> …books are just one way of looking at the world. Some people can open a book and just memorize it, but I can't do that...And I'm not being anti-intellectual at all. I mean books are my tool. But what I am saying is, how do you get into something? I think it is seeing the beauty in it...When you see the beauty in natural systems...That's where I am going with all of this. It's the issue of beauty, for me anyway. (Scientist)
>
> There is awe and wonder in every aspect of nature. You can find it in a grain of sand. Who was that, Tennyson, who first pointed that out? But here there is all the story of wonder. Migrations, the wonders of where things move, why they move, why they are here at all, all in proximity to so many people. So we've got a lot of pretty cool stuff here, from swans to Peregrine falcons to shorebirds that nest in the arctic. Some of which will spend the winter off the end of Tierra del Fuego, that are passing through this particular environment. (Scientist)
>
> …with a foundation that deals with understanding nature, more the awareness and insight, they begin to understand how ecology works. They begin to understand about the benefit of biodiversity, and begin to fall in love with it basically. Love, which is an odd attribute in many ways, was something that was seen to be one of the things that was neglected. The things we love are the things we defend. And the things we really care about are the things we really commit to. We would at least make changes in our lifestyles and make adjustments because we love what we are losing. (Scientist)

The notion of beauty and aesthetics in science is often deemed as less objective and anti-intellectual within the highly rational culture of science (Girod, 2007). Yet, comments like these provide evidence for the importance of art and beauty in the lives of scientists and the possibility of how they can inspire scientific research, creativity, and experimentation. Therefore, designing an ecology program that capitalizes on the power and compelling nature of scientific-aesthetic linkages has the potential to deepen scientific understanding while being sensitive to nature's beauty, making learning an intellectual as well as an emotional process. By creating experiences that allow our students to "bond with the natural world, and learn to love it" (Sobel, 1996, p. 10), we can build relationships of care for places close to home. Through a deeper connection to the land, we can begin attending to issues related to our impact on the environment and its sustainability. In his classic essay, "The Land Ethic", Aldo Leopold (1949/1966) eloquently reflects on the need in education for this kind of relationship with the land:

> It is inconceivable that an ethical relationship to land can exist without love, respect, and admiration for the land, and a high regard for its value. Perhaps

> the most serious obstacle impeding the evolution of a land ethic is the fact that our educational and economic system is headed away from, rather than toward, an intense consciousness of land. (p. 261)

The land ethic involves stewardship of the land. In order for anyone to have a land ethic, they must first have an image of land as a living system, a community rather than a commodity (Leopold, 1966). An understanding "that land is a community is the basic concept of ecology, but that land is to be loved and respected is an extension of ethics" (p. xix). This image, combined with the understanding that we are part of that living system, can become concrete with a visit to a local natural area to enable observations of ecosystems and an understanding of how they function. Incorporating activities that included both knowledge and a sense of awe and respect for nature was encouraged by scientists, with promotion of a stewardship role for students considered to be one of the primary goals when building science education programs for urban natural areas.

> That's where the hands-on, embedded in the context—wading in the wetland, going to a site a couple of times so that they can begin to identify with it—comes in. It's an old cliché that you learn about something, you appreciate it, you appreciate something, you end up loving it and you'll take care of it. And if they are involved with it they will glom onto it, and it will become their own. They will become protective of it. (Scientist)

With regard to the affective component, emotional involvement is a factor that plays an important role in the definition of attitude (Yount & Horton, 1992). Furthermore, attitude influences behaviour and motivation. Therefore, the way in which the ecology field study is presented and undertaken will have an effect on student attitudes. Feelings of interest and value that may occur when getting to know an ecosystem can have a collateral effect on student attitudes toward defence and protection of the ecosystem (Manzanal, Barreiro, & Jimenez, 1999).

> Part of the curriculum is to have the students gain an appreciation for science and for the environment. But even while on site...you could do all the testing, the phosphorous, dissolved oxygen and all that kind of stuff, but just seeing the actual life there has an impact as well. Seeing the herons, the geese, swans, and black birds...all these different things you wouldn't see in your backyard that many of these kids have never seen before. So even being on site and seeing that kind of thing I think would cause them to think, "Well, wait, maybe this isn't just a big slew, maybe this isn't just a big bunch of weeds and algae, and there is more life here and it is important for a number of reasons." And then to do obviously the tests at the same time so they get a better appreciation for the science: Ok, what does that amount of dissolved oxygen mean and all that kind of stuff. (Teacher)

> I've placed too much emphasis on the data collecting in the past couple years. I think the role playing and discussing different issues and perspectives around the watershed is more important. The data collection has value, there

> is no doubt about it. But I think it is a small part of it. It gives them something to do. But we want them to have an experience where they become more emotionally attached to the area. It's almost like our excuse to get them out to appreciate the area. (Teacher)

## READING THE DISCIPLINES

When we look at Big Lake in Figure 5.1, we don't see Biology, Chemistry, or Physics. These are constructs put in place to guide the curriculum. However, when teachers take students to a natural habitat, it is invariably to cover a part of the curriculum defined by those constructs. The curriculum guiding the development of teacher resources of Big Lake was the Biology 20 curriculum as part of the program of studies developed by Alberta Education. For example, according to Unit B: Ecosystems and Population Change of the Biology 20 course, under general outcome 1, specific skill outcome B1.2s, students will:

> Conduct investigations into relationships between and among observable variables and use a broad range of tools and techniques to gather and record data and information [by] perform[ing] a field study to measure, quantitatively, appropriate abiotic characteristics of an ecosystem or ecosystems and to gather evidence for analysis, both quantitatively and qualitatively, of the diversity of life of the ecosystem(s) studied. (Alberta Education, 2007, p. 29)

K-12 curricula around the world are primarily designed to teach students specialized knowledge within the context of specific subject areas such as described above. Consequently, teachers are educated within similar disciplinary frameworks to develop competency in teaching a curriculum framed by those disciplines. Disciplines are, however, constraining because they delimit the range of research questions, the kinds of methods used, and the types of answers that are considered legitimate. Consequently, scientific research is now becoming much more interdisciplinary. If we examine the current global environmental challenges we are facing, emerging solutions are based on interdisciplinary knowledge and the skills to synthesize and analyze knowledge across disciplines.

The Biology 20 curriculum described above leads us to a model of teaching that presents a view of the world that is false and one that leaves students ill-equipped to live in a world in planetary crisis. Most educational systems tend to categorize and analyze pieces of knowledge rather than weave them together in a way that makes sense of the world. This is particularly true in teaching aquatic ecosystems, as complex socio-scientific and environmental issues are pedagogically challenging for science teachers and difficult to integrate into the science classroom (Gayford, 2002; Tytler, Duggan, & Gott, 2001). Teaching about environmental issues requires an interdisciplinary approach—an integration of science disciplines, as well as social, economic, political, and other non-scientific issues (Gayford, 2002; Jenkins, 2003; Schreiner, Henriksen, & Hansen, 2005).

These other disciplines require the addition of knowledge and views that might not be able to be read at Big Lake, but that rely on secondary information collected from elsewhere either at a later date or in advance of a visit. The addition of extra information and material could become overwhelming for teachers and students with Big Lake metaphorically becoming too big.

The idea that the environment is too big a concept to study has been considered by many to be a limiting factor for environmental education (Cooper & Palmer, 1992). Nevertheless, it is through the broadening of the disciplines that critical environmental literacy becomes possible. Bishop et al. (2000) regard critical environmental literacy to involve the capacity to engage in debate about environmental issues at an ideological and philosophical level, to unpack the text. Such capacity carries with it the possibility of effective and reasoned political action with respect to the environment. Critical literacy is essential for effective action (cf. Habermas's conception of critical emancipatory knowledge, Habermas, 1978), yet is impossible if not grounded in a good level of functional and cultural environmental literacy (Stables, 1998).

The scientist and educator perspectives revealed a complex, multi-dimensional, and dynamic nature of such partnerships. Different lenses were used to read and view the scientific and educational potential of Big Lake. Indeed, scientists and teachers read Big Lake in different ways. This demonstrates the value of having collaboration so that the varying and multiple perspectives can be integrated. Gaining an understanding of the distinctive expertise that scientists and educators bring to the partnership is critical. As science educators and scientists collaborate, they can help each other understand the connections between scientific knowledge, student learning, and attitudes towards science. However, these objectives cannot be fully achieved without a combination of both the scientists' expertise and the teachers' pedagogical expertise and experience. And so, in addition to sharing a keen willingness to enter into a science-education partnership, expanding the boundaries of each other's professional culture is essential. Only then is the partnership suitably positioned to translate and communicate the interdisciplinary science of a particular natural area into a site-specific science education resource.

Therefore, an increased understanding of scientist and educator perspectives may facilitate scientist-educator interactions, and, with both parties exhibiting greater initiative in seeking out each other's professional expertise, the successful creation of new opportunities for future collaboration can be enhanced. In addition to establishing the merit of forging new partnerships between scientists and educators to develop science educational resources, this research hopes to prompt further dialogue, and encourage more educators to consider the importance of linking local natural areas to their science education program. Developing science programs that have students engage in inquiry, through participation in fieldwork in a local natural area, attempts to transcend the traditional dissemination model of science education by providing opportunities for students to learn through experiential, hands-on activities while providing a unique balance among the different dimensions of scientific and environmental literacy.

All students need assistance at developing sensory awareness and teachers ought to be on the alert to point out environment experiences, so as to educate each student's individual sensory pathways. Students need to be helped to appreciate and read patterns, movements, sounds, shapes, colours, and textures, in the immediate world around them. Our environment is full of information to be gathered, if students have developed awareness to take advantage of such events. As teachers we need to help our students develop the awareness and critical skills to read and appreciate their environment both aesthetically and scientifically.

## READING FOR PEDAGOGY

The teachers clearly read Big Lake with pedagogic eyes, which is hardly surprising. The logistical, practical, and safety elements of teaching were clear priorities for teachers. For example: Where are there convenient and safe access points to sample the lake? Where might a bus park? Where are the nearest washrooms? Where would students go if it rained? The requirements for keeping students safe and comfortable were clear overarching factors. This kind of reading can be connected to Goodwin's notion of professional vision (Goodwin, 1994), understood as an expert ability to read the signs of the environment, for example, of an archaeological dig. Whilst scientists did not read the danger or express any concerns about such safety and logistical aspects, they did acknowledge and accept their own limited pedagogical knowledge, and recognized the value in having education specialists involved in program planning for this project. This study has clearly indicated that collaboration between scientists and educators brings contrasting perspectives that are essential in the development of science teaching resources. In terms of literacy, the collaboration facilitates the inclusion of critical and cultural literacies in addition to the functional literacies more typically represented in science resources.

Like print books, Big Lake can be read over and over by a range of readers, each reader potentially interpreting the text in different ways. The text at Big Lake, however, is dynamic and changes with the seasons and years. Regularly reading Big Lake can inform, educate, and culture a love and passion for the natural world. The analogy of reading the environment challenges us to reconsider what counts as reading, but can also help reassure both students and teachers that it's acceptable not to know a book before you read it, and that it's not necessary to remember the name of every character in the book. What is important is to enjoy the read and deepen an understanding and empathy for the natural systems we are part of.

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# III. VISUALIZATIONS IN SCIENCE AND MATHEMATICS

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# 6. VISUALIZATIONS AND VISUALIZATION IN MATHEMATICS EDUCATION

## INTRODUCTION

There is no shortage of interest in visualization in mathematics education. Mathematics textbooks are filled with pictures, diagrams, and graphs. There are video lessons available for countless topics. Graphing calculators have become commonplace in secondary school classrooms. Dedicated computer programs such as Geometer's Sketchpad, Mathematica, Maple, and the open-source programs that are intended to replicate many of their functions are now in use in secondary and postsecondary mathematics classrooms. Data visualization programs are becoming common in statistics classes. And there are countless applets available on line. Given the sheer volume of visualization materials available for mathematics education, it is surprising how little empirical support there is for their use. In addition, there are no robust educational theories of how to use best visualization in mathematics education. There are two powerful but conflicting cognitive theories of visualization, and both point to some practical application of visualization in spite of their mutual inconsistency.

This chapter begins with a brief summary and synthesis of the best empirical evidence regarding the use of visualization in mathematics education and illuminates this evidence with appeals to cognitive theory and reports of current educational practice. In spite of disagreement on the cognitive mechanisms that make visualization possible, there is defensible educational research that provides some guidance to teachers. As a backdrop to this research summary we pose a fundamental riddle of visualization in mathematics education: How is it possible to make abstractions visible and why would we want to do so?

The second part of the chapter looks at how objects for mathematical visualization are developed and promulgated within the field. Developers and practitioners are not waiting for educational theory and empirical study to guide them; they simply move forward based on their practical experience and informed inferences about what is useful and why. The chapter closes with recommendations for future research.

## OBJECTS, OPERATIONS, AND INTROSPECTION

We found 23 explicit definitions of visualization and related terms, such as "imagery" and "visual aid", published between 1974 and 2009 (Phillips, Norris & Macnab, 2010, pp. 23–26). The definitions were sometimes vague; often they were contradictory with other uses in the literature. The word "visualization" was sometimes used to describe a

*Stephen P. Norris (Ed.), Reading for Evidence and Interpreting Visualizations in Mathematics and Science Education, 103–122.*

visual representation; sometimes it was used to describe the use of such a representation; and sometimes it was used to describe the cognitive activity of imagining a visual representation. We follow our use in the earlier review and recommend making these distinctions explicit by adopting the following three terms: 'visualization object', 'introspective visualization', and 'interpretive visualization'.

– Visualization Objects are "physical objects that are viewed and interpreted by a person for the purpose of understanding something other than the object itself." (Phillips et al., 2010, p. 26)
– Introspective Visualization is "an imaginative construction of some possible visual experience" (Phillips et al., 2010, p. 26) in the absence of a visualization object. Introspective visualization focuses on "mental objects pictured in the mind." (Phillips et al., 2010, p. 26)
– Interpretive Visualization involves the interpretation of meaning from visualization objects or introspective visualizations in relation to "the person's existing network of beliefs, experiences, and understandings." (Phillips et al., 2010, p. 26)

These distinctions separate physical artifacts or visualization objects from cognitive actions (i.e., interpretative and introspective visualization). In other words, visualizations are distinguished in terms of physical objects (i.e., illustrations, animations, computer-generated displays); mental objects pictured in the mind (i.e., mental schemes, mental imagery, mental constructions, mental representations); or cognitive processes (i.e., cognitive functions in visual perception, manipulation and transformation of visual representations by the mind, concrete to abstract modes of thinking, and picturing facts). "Visualizations can be realistic or schematic, and may depict the directly visualizable or the non-visualizable" (Phillips et al., 2010, p. 18). These distinctions are important for understanding the context of visualizations and for establishing effective applications of visualization in the mathematics classroom.

In mathematics education, simple diagrams historically have been important visualization objects. In addition to images presented to students, there are also visualization objects produced by students themselves, and students may introspectively visualize. Dwyer (1968) noted that realistic detail can interfere with students' ability to construct their own drawings. Although Dwyer was not working in a mathematics context—he was examining undergraduates' ability to abstract information about the human heart—he made an observation that will be echoed several times in this chapter. Dwyer argued that, when a visualization object intended to support information or inferences that are to be later produced contains too much detail, students will have difficulty differentiating the relevant from the irrelevant. It now appears that the ability to interpret visual representations is a far from trivial task for most students. Teachers and the producers of educational materials must be aware of the importance of simplicity and efficiency. In producing animated displays, Lee, Plass and Homer (2006) devised a visual complexity metric to assist their decision to divide a display into two simpler displays. This general consideration suggests other applications in education; further research is in order. We suspect that the issue of complexity will be important for some other types of display: schematic diagrams, for example.

Finally, although little is currently known about the relative merits of teacher-produced and student-produced visualization objects, we suspect that they may perform some differing functions in student learning, and that there may be important pedagogical implications of the choice to provide or the choice to have students create visualization objects.

## WHEN DO VISUALIZATIONS HELP?

A recent review of scholarly articles dealing explicitly with visualization in mathematics education found two central themes. First, there is a theoretical question about the function of visualization objects as mathematical objects. Second, there is the practical issue of the effectiveness of visualization for learning and doing mathematics. The issues overlap and interspersed throughout is reflection on the appropriate goals of mathematics education (Phillips et al., 2010).

Both the propensity to use visualization and the style of visualization object preferred have been shown to vary with prior mathematical achievement. Presmeg (1986) explored the use of visualization objects by junior high school students, examining differences of use between gifted students and their peers. She “found that pupils whose achievement was singled out as being outstanding (7 pupils, out of 277 pupils) were not merely ‘often’ but were ‘almost always’ nonvisualizers” (p. 297). Even loosening her criterion to students who were identified as “very good” at mathematics (27 out of the 277) only 5 were active visualizers and the remaining 18 were not. Perhaps this result should have been expected. A century earlier, Francis Galton surveyed the Royal Society to find out how those eminent scientists and mathematicians made use of imagery. Galton “found that the great majority of the men of science…protested that mental imagery was unknown to them” (1880, p. 302). In (unsystematically) surveying the general public, Galton found just the opposite result to what he found with the Royal Society: adults and children “declared that they habitually saw mental imagery and that it was perfectly distinct to them” (p. 302). Galton interpreted this difference to be the result of cultivation of habits through education. “The highest minds are probably those in which it [the ability to visualize] is not lost, but subordinated, and is ready for use in suitable occasions” (p. 304). This remains an important hypothesis to this day.

Presmeg (1986) came to conclusions similar to Galton’s. She observed that “visualisers are seriously under-represented amongst high mathematical achievers at senior high school level” (p. 297), noting that much use of visualization that she observed was related to single case problems and that there was little academic payback in their extended use. She further hypothesized that the inverse relationship between the propensity to visualize and achievement in mathematics could be an artifact of the way that mathematics is taught and assessed. It could be that if mathematics were taught in visual ways and if visual representations were an essential part of assessment and grading, that students may begin to work and to communicate more often in this way. As we shall see later in the chapter, it is just this belief that motivates much of the current explosion in computer-based visualization in mathematics education.

Van Garderen (2006) found a subtle distinction in the use of visualization in mathematics by students identified as learning disabled, average achievers, and gifted. Unsurprisingly, she found that gifted students outperformed the others on spatial tasks. In contrast to Galton's and Presmeg's findings, the use of visual images was positively correlated to the solution of word problems. Most provocatively, she found that there was a pronounced difference in the types of imagery exploited by higher-achieving students than was found with average and learning disabled students. Mathematically gifted students tended to abstract relevant information into schematic representations to provide a working object, while other students did not make this simplifying move and tended to work with images that preserved visual realism. "The use of schematic imagery was significantly and positively correlated with higher performance on each spatial visualization measure; conversely, it was negatively correlated with the use of pictorial images" (p. 496). Van Garderen's results are consistent with some general findings by Knauff and Johnson-Laird (2002), who experimentally demonstrated that extraneous detail burdens reasoning and undermines other benefits that visualization might bring about. This is so, they argue, because irrelevant content must be processed and it can lead learners in unpromising directions. The implication is that teachers should in some contexts restrict the scope and structure of visualization objects to only information essential to the task at hand. Further it suggests that teachers should explicitly teach students how to distinguish the relevant from the irrelevant.

It is worth reflecting on Dwyer's (1968) research on the ability of undergraduates to learn from diagrams of the human heart. Dwyer found that highly detailed drawings and photographs impeded students from learning about the anatomical detail of the heart. Simplified and schematic representations facilitated the students' ability to observe, understand, and generalize. Even though Dwyer did not explore differences between high- and low-achieving students, his results are supported by the explicitly mathematical research noted above.

Another variation on the theme of relevance was proposed by Richland, Zur & Holyoak (2007), who analyzed the use of analogies in eighth grade mathematics teaching in Hong Kong, Japan, and the United States. The countries were chosen for contrast because of Hong Kong's and Japan's high achievement on the TIMMS international comparison test, and the United States' relatively low ranking when compared to other industrialized nations. The study found little difference in the quantity of analogies used in the three countries, but found considerable difference in the support of the analogies with visualization. "Hong Kong teachers were almost twice as likely to prompt mental and visual imagery as were U.S. teachers, and Japanese teachers were even more likely" (p. 1129). While this is hardly conclusive, it does suggest an important area for further consideration. In the cases Richland et al. studied, visualization was utilized as an illustrative strategy, not as an end in itself. When the visualization is part of an explanatory strategy that links a mathematical concept to an analogous situation, they hypothesize, there may be benefits to both skill learning and understanding. Clearly, further experimentation and analysis is required before the consequences of this difference in approach can be fully understood.

It is difficult to find many conclusive educational recommendations from the research literature. It appears that there is a negative relationship between the willingness to use visual imagery and mathematical achievement. It does not follow, of course, that the use of imagery ought to be discouraged. There is no evidence that visualization or visualization objects are causal in the development of mathematical ability. Nor is it clear that mathematical ability discourages the use of visualization. It is possible that all that is being observed is an artifact of the participants' mathematics education or of the tasks with which they were provided. What does appear to be the case in these studies is that, given the choice, more successful students currently do not opt for visualization as often as less successful students. Nonetheless we cannot ignore Van Garderen's (2006) research that suggests that higher achieving students are able to exploit visualization when required to do so. There appears to be a discrepancy between what better students are able to do and what they choose to do. When visualization is utilized, better students strip essential coding material from visualization objects, while lower-achieving students do not. It remains an open question whether this is a teachable skill (but we see no theoretical or practical reasons why not) and whether improved ability to abstract schematic information necessarily or even probably leads to improved mathematical outcomes. Vekiri (2002) notes the possibility that while benefits from visualization are a function of student prior achievement, it is possible that the benefits taper off to a point where very strong students gain nothing from visualization in some contexts. For those cases where visualization is deemed to be desirable, Presmeg (1986) advocates that teachers make explicit the relationship between visualization objects and other verbal and symbolic representations of their referents. It is likely that different students require different levels of explication, based on each student's previous experience, mathematical achievement, and perhaps innate and developed abilities in visualization.

It remains unclear whether a change in the style of presentation and assessment in mathematics to a more visual mode would lead to different outcomes in student achievement than do the currently dominant symbolic and verbal modes. If visual representations of mathematical results were to displace some or all of the currently used symbolic and verbal representations, it is not clear who would benefit. Even though it has been repeatedly shown that higher achieving students do not currently use visualization as much as do lower achieving students, Van Garderen's (2006) results suggest that they will continue to outperform their peers should such a pedagogical shift occur. It remains to be seen whether new problems of inequality of educational outcomes would result from changing instruction and assessment to visual modes. The evidence to date does suggest, though, that the teacher should be playing an active role in the selection of visualization objects, in explicitly teaching students how to abstract relevant information from them, and in how to make them maximally informative and minimally distracting.

### *Cognitive Theories of Visualization*

In a wide-ranging and insightful survey of the cognitive psychological literature dealing with visualization, Vekiri (2002) categorized currently relevant theories as Dual Coding, Conjoint Retention, and Visual Argument. We will follow Vekiri's overall organization, but we will collapse Dual Coding and Conjoint Retention theories under the rubric *semantic theories*, and refer to Visual Argument theories as *syntactical*.

Semantic theories of visual processing hold that however it is that brains store, manipulate, and retrieve the cognitive or mental objects of visualization, they treat these objects as tokens of meaning. So, if a child mentally works with a visual representation of a tree, the cognitive objects that are part of the child's mental machinery will be meaning-bearing objects that contain some direct representation of the tree. Well-chosen visualization objects, on this view, are explicitly meaningful in ways that verbal or other objects are not. In contrast, syntactic theories hold that the child's cognitive objects are no different in type from language or some other form of input, but that they have different computational properties as the basis of operations. For the advocate of syntactic theories, well-chosen visualization objects are easy to manipulate or have easily identifiable features that permit mental operations.

Semantic theories propose that when a student has mental access to both verbal and visual representations, then it becomes possible to access the same information for different purposes and at different speeds, depending on task requirements. If this is so, then it is important that teachers and students develop awareness of the strengths and limitations of their representations—whether verbal or visual—and make choices based on defensible grounds. It seems unlikely that visual representations can contain mathematical and cognitive content identical to that of verbal or symbolic representations. Defending syntactic theories, Pylyshyn (2003) makes similar recommendations, but based on very different grounds. Pylyshyn proposes that brains do not store visual information, or any information for that matter. Instead, he suggests that brains store procedures. The efficacy of visualization, for Pylyshyn, is that well-chosen visualization objects have computational properties that can be efficiently accessed. This is consistent with Galton's (1880), Presmeg's (1986), and Van Garderen's (2006) observations that higher-achieving mathematics students are more likely to use informationally minimal schematic visualizations than are lower-achieving students.

Pylyshyn (2003) lists five instances where his syntactic model suggests that visualization objects are beneficial to learning and to the application of knowledge:

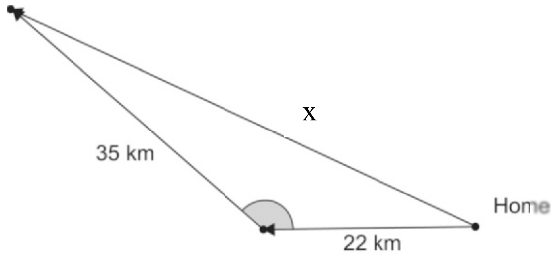
- They are systematically structured to exploit visual operations.
- They are guides for derivational milestones.
- They assist visual generalizations.
- They provide ways to track instances and alternatives.
- They provide external memory of spatial patterns. (pp. 439–455)

Each item on Pylyshyn's list is an instance of visualization being utilized as a sort of calculator, or scratch pad. The point is that visualization can provide a means by which students can organize mathematics and perform concrete operations on it.

Empirical research into the application of semantic theories of coding in mathematics learning environments typically involve comparing mathematical performance in learning a concept verbally and symbolically versus learning verbally, symbolically, and pictorially. Suh and Moyer-Packenham (2007) went a step further and tested groups of Grade 3 students that learned two mathematics units—fractions and algebra—one in a condition with computer visualization and one in a condition without. Students were assigned randomly into treatments. Students who learned with visualization outperformed those learning without. But it is hard to see how this supports a semantic interpretation of visualization as they claim. If their design is sound, the best we can conclude is that this material was better learned with the visualization than without. This could be because more time was spent on one method than the other. It is not obvious that the cognitive and pedagogical content of the two styles of presentation is equivalent. Most significantly, it is not clear that the modes of representation were encoded, retrieved, and used in entirely distinct manners.

It is possible to reinterpret Suh and Moyer-Packenham's results in terms of a syntactic theory of visualization. If we agree with the conclusion that the material from either unit was better learned in conjunction with visualization, why do we not believe that the visualization objects were superior for manipulating relationships than were the symbolic or verbal objects? More plainly, if a student were to use, for example, Figure 6.1 to solve the problem it represents, how can the solution to the problem indicate how it was processed in the student's brain? Did the student have two distinctly stored representations, each of which was meaningful in different ways? Or did the student have two distinct procedures stored in the same manner, each of which allowed for different sorts of mental operations? We see no way to adjudicate this matter based on the available evidence.

One day cognitive science may solve the question of whether visualization objects are processed semantically or syntactically or whether both of these families of theories fail to fully capture what is going on in brains. When that question is settled, it may be possible to use the best cognitive models to construct conditions for improved mathematical learning. From the point of view of practical pedagogy *today*, it probably doesn't matter which theory we adopt, if any is necessary at all.



Jana leaves her home and travels 22 km west. She turns $43^{\circ}$ toward the north and travels another 35 km. How far is she from her home at this time?

*Figure 6.1. A simple trigonometric representation.*

### *Visualization as a Computational Aid*

One common use of visualization in mathematics education is a diagram that assists the student to organize and account for information. Figure 6.1 is a simple and clear example of this; standard symbols represent directed distances and angles, with appropriately placed numbers and symbols indicating the given or calculated values relevant to the problem. Once the student has made the appropriate transformation of words to mathematical ideas, the graphical symbols are intended to help in the storage, retrieval, and manipulation of the relevant information.

Figure 6.2 comes from an interactive web module for teaching mathematical modeling (Wonham, Macnab, Norris, & de Vries, 2008). The module takes students through development of a mathematical model of the spread of the West Nile virus in interacting populations of crows and mosquitoes. The diagram shows how the populations of mosquitoes and crows each can be divided into two groups: those infected with the virus and those susceptible to infection. Students are led through the diagrams to produce differential equations that model the population sizes and their rates of change.

Figure 6.2 exploits all five uses on Pylyshyn's list. The diagram uses closed figures to indicate population exclusivity and arrows to show movement between groups over time. It shows relationships between variables and their referents, and arrow direction indicates the sign of each rate of change.

To make sense of Figure 6.2, the student must know something both of the biology of the situation and of the basic mathematical ideas being modeled. The schematic nature of the diagram focuses attention away from the physical situation and directs it toward the mathematical objects that are being abstracted. Populations are interrelated in terms of their size and their rates of change.

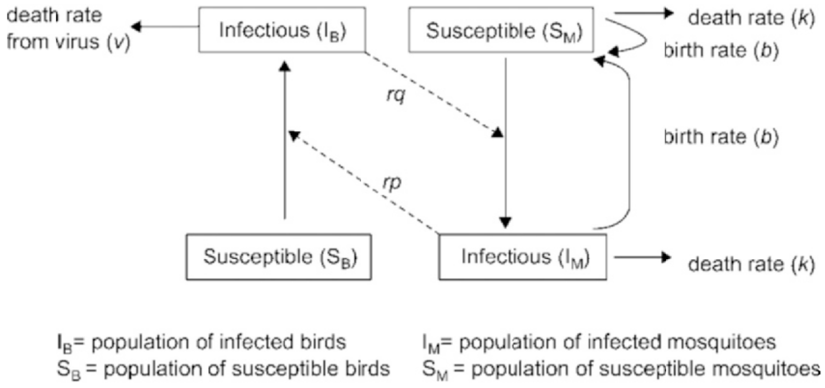


*Figure 6.2. A schematic diagram from a teaching module on modeling the spread of the West Nile Virus.*

The austere diagram is designed not only to show relationships, but to relieve memory. The student can explore one relationship while ignoring others, secure in the knowledge that the other relationships won't be forgotten. Once the diagram is comprehended by the student, it is a relatively straightforward matter to express the differential equations that it is meant to encode. The diagram offers no help in the solution of the system of differential equations, however.

We will develop two simple equations from the diagram to show the computational assistance that it can give. Consider the student question: How many mosquitoes are included in this model? We note that mosquitoes are encoded as *M* in the model. Since the model is designed to account for every crow and every mosquito in the populations under study, we can simply look at the diagram, find all the *M*s and add them up. The only mosquitoes listed are those that are infected $I_M$ and those that are susceptible to infection $S_M$. Thus, if $N_M$ is the total number of mosquitoes, the student should be able to write

$$N_M = I_M + S_M . \tag{1}$$

Although equation (1) is trivial, it does show the usefulness of the visualization object for exploiting visual generalizations, storing derivational milestones, and for tracking instances. This becomes more important as students look at more complicated relationships. When asked to account for the rate of change of the number of crows that are currently susceptible to infection $(dS_B / dt)$, the usefulness of the visualization object becomes more evident. Briefly, the right hand side of the equation is composed of: *r*, the biting rate; *p,* the probability of infection from a bite; $I_{M,}$ the number of infectious mosquitoes; and $S_B / N_B$, the proportion of susceptible crows in the population.

$$\frac{ds_B}{dt} = -rpI_M \frac{S_B}{N_B} \tag{2}$$

Hopefully some readers are having an "aha" moment—that instant of recognition or of understanding. Certainly teachers would expect some students to have that here. While the utility of the visualization in accounting and computing is clear, so is the possibility for the facilitation of understanding. From the perspective of the visual imagery hypothesis, the understanding is a consequence of improved computation and organization. As we shall see in the following section, a proponent of the dual coding hypothesis might analyze the situation differently. On that view the spatial organization of the model provides a different means of grasping the relationships than does natural language or mathematical symbols. This difference suggests to dual coding advocates that the diagram facilitates understanding by being appreciated distinctly from other ways of perceiving the situation.

### *Visualization for Understanding*

Can we make a case for the use of visualization in developing mathematical understanding? Examine the base-10 blocks in Figure 6.3.

As computational aids, they are weak; it is much more efficient to use the pencil-and-paper algorithm to multiply 3 × 14 than it is to model the situation with blocks. The point of the blocks is that manipulating them by hand or drawing them on paper or dragging images with a mouse is supposed to help a student to develop understanding of both number and operations. With the blocks, the student can see that the number 42 can be decomposed into 4 groups of 10 and 2 singletons. The student who understands this understands something significant about the number 42. The teacher, presumably, is preparing the student to generalize the basic structure of base-10 numeration. Similarly after multiplication, the student learns the procedure of grouping the singletons and converting 10 of them into a 10s block by learning to see the relationship, rather than blindly following an algorithm. Of course, much of this is dependent on explicit instruction and appropriate internalization by the student.

The student understands a concept insofar as he or she can produce an account of it in response to queries and can set this account in a context that is comprehensible to an interlocutor (Norris, Macnab & Phillips, 2007). This suggests that when visualization is used to develop mathematical understanding, both visual and other expressive faculties are in play. Most often, the connection involves verbalization of mathematical concepts as represented visually. There is a comforting parallel to this view of understanding and the dual coding theory of visualization. If judgments of student understanding are related to the student's ability to provide accounts of the matter in dialogue, then it is desirable that the student have access to complementary and robust means of expressing mathematical ideas. The separate coding of verbal and pictorial depictions

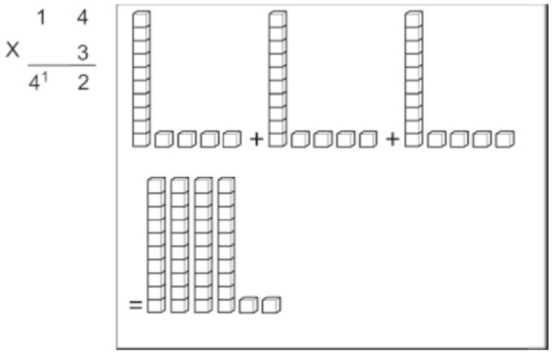


*Figure 6.3. Two representations of 3 × 14 = 42.*

would support a robust educational theory of teaching for understanding. It is from this insight that the dual coding hypothesis finds justification for suggesting that well-chosen visualization objects and activities support the development of mathematical understanding. This is the main idea suggested in the final comments of the preceding section. The development of understanding is an important student outcome, regardless of the neurology that underwrites it. If it is the case that the use of visualization can foster this development, then it is incumbent on educators to find ways to make use of it.

Figure 6.4 comes from the 12th century Indian mathematician Bhaskara. Evidently, Bhaskara believed the diagram to be so rich with meaning that he wrote nothing other than "Behold!" under it. What is it that we are meant to behold? The diagram seems to offer a justification for the Pythagorean Theorem. A reader must supply some geometry before this inference can be made. Regardless, this visualization object clearly is intended to assist a learner to understand both the content and a justification of a mathematical result. Vekiri's point that there should be a connection between image and text is well taken. However, there is no principled reason that the learner cannot supply the text, even introspectively. On the other hand, the student who is unable to supply this text cannot develop understanding in this situation; here the teacher must provide some sort of explanatory material. The view of understanding that we have offered suggests that the diagram itself is insufficient to support judgments of understanding. That is, not only would the diagram be insufficient for a student to show understanding of the Pythagorean Theorem, but the diagram would be insufficient to teach the theorem to the student. What is missing is linguistically and/or symbolically structured text to complement the visualization.

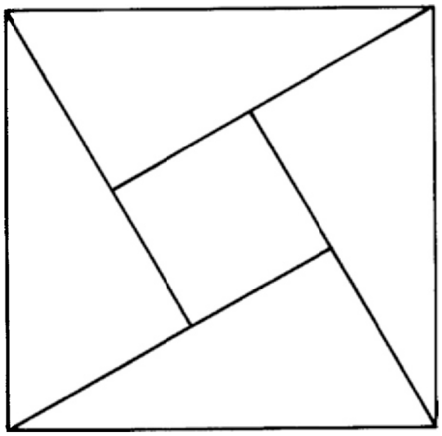


*Figure 6.4. A "proof" of the Pythagorean Theorem, ascribed to Bhaskara who gave no text other than "Behold!" (Eves, 1969, p. 188).*

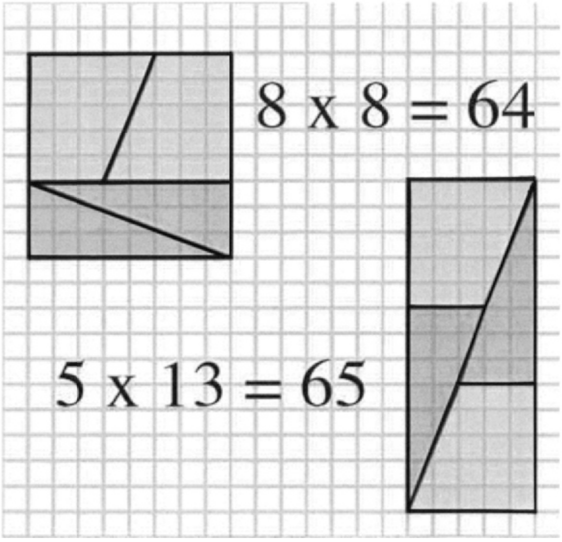


*Figure 6.5. A “proof” that 64 = 65 (Bradis, Minkovskii & Kharcheva, 1999, p. 162).*

Figure 6.5 provides a superficially convincing geometrical argument that 64 = 65. As with Bhaskara’s diagram, this one requires that the reader dissect the rectangles into smaller figures and to compare areas. Suppose a student was to encounter this diagram and say that yes, it does indeed show that 64 = 65. Hopefully the teacher would not take this as evidence that the student knows this proposition. But why not? If the student has base-10 block grounds to believe that 64 ≠ 65 and visual evidence that 64 = 65, how is he or she to choose between the results? The judgment of understanding is contingent on the student’s ability to justify the results to an interlocutor. And here it appears that perhaps students are on shaky ground in both cases. It is an interesting empirical question whether most students can justify the results of base-10 block arithmetic. Perhaps it is more difficult to teach understanding than is generally believed. Figure 6.5 surely requires justification, if for no other reason than its result comes merely from “it looks like it.”

Figure 6.5 provides a powerful cautionary tale for advocates of visualization in mathematics. A visually compelling account is not necessarily a mathematically accurate one. While some teachers may be content to use Figure 6.4 to justify the Pythagorean Theorem, we hope that none would use Figure 6.5 to convince students that multiplication is inconsistent. The persuasiveness of the diagrams is what makes non-visual mathematics necessary in both cases. Figure 6.4 should not be mathematically compelling—or educationally persuasive—without a verbal and/or a symbolic articulation of an argument relating the components of the depiction to the result. Figure 6.5 should be rejected not because its claim seems to be wrong, but because *it contains no argument*. Figure 6.5 appears to be simply translating and rotating pieces from one diagram to the next. In order for the claim of the diagram to be believed, it must be shown that the pieces are in fact congruent pieces that have been translated and rotated. Arguments to that effect are evidence of understanding.

This short survey indicates the narrowness of research within both the semantic and the syntactical camps:

> Semantic theorists focus exclusively on research that indicates that students can acquire knowledge from combining linguistic and visual representations of the same or closely related phenomena. Syntactical theorists focus on visual imagery that is used entirely as an external reference. Neither group seems to be interested in the others' research. The results suggest that both groups have found important educational uses for visualization. Well-designed visualization objects are useful computational aids when they are used to relieve the student's working memory of some of its load. Other well-designed visualization objects are useful as an adjunct to other means of acquiring knowledge, such as reading text or listening to language. It remains unclear how this is accomplished in the brain, but it is clear from the extant research that educators have two powerful theoretical bases for utilizing visualization in the classroom. (Phillips et al., 2010, p. 41)

### *Dynamic Visualization Objects*

Vekiri (2002) noted that there was no standard system for classifying visualization objects (p. 264). We have found no major improvement to date. Above we have divided visualization objects and visualization by function—sometimes the purpose is computational and sometimes it is to aid in understanding. But this is insufficient for the wide array of objects and activities that are possible. One clear distinction that does appear in the literature separates static from dynamic visualization objects (Phillips et al., 2010, ch. 5). Static visualization objects are the pictures, diagrams, graphic organizers that are well known in schools, even if, as we have seen, they have not been extensively studied. Static displays are rapidly being displaced by dynamic displays that change over time.

Increasingly, dynamic representations are employed by teachers to structure mathematical concepts for students. An important political push in this direction began with the National Council of Teachers of Mathematics *Principles and Standards for School Mathematics* (2000). In that influential document, the belief that "electronic technologies—calculators and computers—are essential tools for teaching, learning, and doing mathematics" (p. 24) was presented as self-evident. Neither theoretical nor empirical support for this contention is found in the *Principles and Standards*. Although NCTM's statement is strong, it is tempered by the recognition that "the effective use of technology in the mathematics classroom depends on the teacher. Technology is not a panacea" (p. 25). The independent curricula of the International Baccalaureate Organisation and Advanced Placement immediately followed the NCTM's lead and mandated the use of graphing calculators in their mathematics courses. Interestingly, both programs currently implement two separate examinations for each student: one using the calculator and one in which it is prohibited.

In spite of a lack of consensus on the appropriate use of visualization in education, computer-based visualization objects are being deployed in a variety of contexts. Many computer- and video-based objects appear not to have been created with any particular educational or cognitive theory in mind. The educational market is apparently content to put forth products in the belief that they will be useful. In addition to commercial products, a number of public domain products are finding their way into education, such as the open-source program GeoGebra (www.geogebra.org).

Vavra et al. (2011) found very little empirical support for dynamic visualization in science education: “a significant attribute of dynamic media is its ability to stimulate student interest and engagement. However, it remains unclear whether dynamic media enhances the learning and understanding of science concepts” (p. 25). The situation is much the same in mathematics education. There are many products and many theoretical articles, but to date there is little empirical data to indicate whether today’s computer technology is actually making a difference in the quality of mathematics education at any level.

## VISUALIZATION AND MATHEMATICS: A PUZZLE

What is the point of visualization in mathematics? Empirical research focuses on two main areas of mathematics education. One area deals with the use of visualization to promote mathematical understanding; the other with the use of objects to assist in mathematical application or computation. Each of these research areas presents a different face of the same question: what is gained by translating abstract mathematics into a singular concrete instantiation?

If mathematics is abstract, how can it be visualized? One of the distinguishing features of mathematics is that it is essentially stripped of physical context. The equation $3 \times 14 = 42$ is not about apples or distances or any physical objects or their properties. The elements of $3 \times 14 = 42$ are numbers, an operation, and a relationship. Of course, young students are not first taught mathematics at this high level of abstraction. They usually deal with countable objects, with physical measurements, with models such as base-10 blocks, and eventually with abstract symbols.

Figure 6.3 shows two representations of the computation $3 \times 14 = 42$. The first is simply Hindu-Arabic numerals in a multiplication algorithm. The symbols are metonyms of the numbers and operations, and their structures make computation simple and transparent—at least to anyone who has received instruction regarding standard meanings of the relevant strokes on paper and the multiplication algorithm. Numerals are useful visual representations because they are easy to read, they reveal information about the base-10 structure of the number, and because they are easily manipulated for computation. Compare the numeral, 42 with its representation in base-10 blocks. The same information is encoded in each representation; in both cases the number is decomposed into $4 \times 10$ and $2 \times 1$. The standard belief is that the block representation is an example of visualization whereas the numeral representation is not, but it is not immediately obvious what would support such a belief.

The distinction is likely due to the practical countability of the block representation. Although numerals are basic, the block representation can be further decomposed into simple unit figures. Although operations such as addition can be performed easily with either representation, the base-10 blocks allow for addition to be seen as the gathering of units, rather than as a more abstract set of operations on more complex symbols. This is the first instance of the puzzle we would like to bring forward: Why might this increased concreteness be desirable? What might educators believe about learning such that it would be beneficial to take an abstraction such as the number 42 and represent it concretely as a collection of unit squares? By what mechanism might we expect students to give up this concrete representation to come to understand number more abstractly? Such questions are not adequately addressed in the extant research literature.

The puzzle can be seen also in the application of mathematics to problems. Figure 6.1 depicts a simple trigonometric problem. In contrast to the base-10 blocks, this diagram takes a concrete problem and increases its level of abstractness. Although the diagram in Figure 6.1 is more abstract than the real-world situation, it has the virtue of being easily taken in at a glance. The difficulty for the student is in knowing which features of the problem are amenable to this sort of abstraction. Jana's name and the location of her home are not significant and do not belong in the representation. But this is not something the novice can know beforehand. The student will have to understand which features of the problem are appropriate for representation and which are not. The student must learn to distinguish the mathematical from the non-mathematical, the relevant from the irrelevant, and the appropriate from the inappropriate. There is much to be taught and learned before apparently simple visualization objects can be useful.

As with numerals and base-10 blocks, the success of the geometric diagram depends on the student's ability to decode conventional symbols in context. Just as the numeral 42 is comprehensible only if one understands place value and the standard interpretation of 10 symbols, so are base-10 blocks comprehensible only if one understands the point of grouping unit squares in this stylized fashion. For the student to understand and use the geometrical diagram in Figure 6.1, the standard meaning of the lines, arrowheads, angle markers, numerals, and variables have to be interpreted correctly. Visual representations are not necessarily transparent to students; considerable knowledge of symbols and conventions may be required for the representations to be meaningful.

Assuming that these simple examples are representative of some of the basic issues of visualization in mathematics—and we believe that they are—a strange puzzle comes to the fore. Visualization is a technique by which the abstract concepts of mathematics are made concrete with the intention that students will be able to make sense of the concrete representations and come to deeper understanding of the abstract concepts. Visualization also appears to be a technique by which the concrete is made abstract so that students can apply mathematics and then later retrieve important implications for the concrete situation. It is puzzling that the same family of techniques allows students both to make the concrete abstract and to make the abstract concrete and that these are both educationally desirable and attainable goals.

## INDUCTION FROM WITHIN THE FIELD

Although it is true that there is not a strong empirical basis for visualization in mathematics education, advocacy and research go on apace. The NCTM's broad support for technology in general is noted above. A good example of this advocacy was provided by Iowa State statistician Dianne Cook (2009), "Incorporating Exploratory Methods using Dynamic Graphics into Multivariate Statistics Classes: Curriculum Development." Cook's stance is that because various professional statisticians use visualization objects for good reasons, we must make these objects explicit and understandable for our students (p. 354). This is an exemplar of a very important way that the field moves forward—with appeal to professional practice, not to educational theory. Cook runs through several examples of visualization objects that are common in introductory textbooks but have been out of use by professionals for years, and in some cases, decades. Cook notes the uses for which current professional visualization objects are put, and makes the case that the student would be better off learning to use such objects from the start, with instruction regarding their construction and interpretation, than they would be learning out-of-date visualization objects and making a translation to current practice later. While we acknowledge that her argument is conceptually based and does not have systematic empirical support, her case is provocative and worthy of further investigation. At the very least, we agree that these reflections on practice, often structured as action research, quite appropriately form an important part of every mathematics educator's ongoing and ever-changing teaching practice.

Cook has an agenda in the use of graphics: she wants students to understand patterns in real-world data. She is not arguing for making mathematical meaning, nor is she advocating practical problem-solving. The point of her argument is that statistics students must learn to find plausible routes in the analysis of data. The practical point is that if professional statisticians use certain tools to explore data, then the tools are likely the best currently available and students are well advised to avail themselves of the best. We suspect that either a syntactical or a semantical case could be made for Cook's agenda; but she makes neither.

The *IEEE Transactions on Visualization and Computer Graphics* is dedicated to the technical problems of implementing dynamic visualization objects. The papers we reviewed from this journal are concerned neither with educational nor with cognitive theories. They work from implicit beliefs about how learning takes place and explicit theories of software development. Learning is typically assumed to be a correlate of user behaviour.

Grammel, Tory and Storey (2010) empirically tested novice use of Information Visualization technology. They noted that novices tended to use depictions with which they were already familiar, and that they had difficulty interpreting graphic displays of data with which they were not already intimate. This indicates that Cook may be overly optimistic in her belief that students can learn to use professional visualizations simply by using them. Further, this result echoes the explicitly educational results from earlier sections of this chapter in which it was noted that visualization objects do not speak for themselves. They are part of a mathematical rhetoric that must be learned. Whether one adopts a semantic or syntactic view of visualization in mathematics education, one cannot but notice that students require explicit instruction on the use and interpretation of visualization objects, whether static or dynamic.

Jankun-Kelly, Ma and Gertz (2007) developed a general model of user activity while working with visualization exploration software on experimental data. They argue that it is essential not only to interact with the tool to explore data, but that it is equally important to record the processes by which this exploration occurs. For Jankun-Kelly et al. (2007) the purpose of recording session activity data is that it will both help designers to improve the tools for users, and it will help users to refine their future activities. This can, perhaps should, lead to important educational innovations. Should such data be available for students using the visualization objects Cook recommends, then it would be possible for instructors to analyze the paths taken to conclusions, to evaluate the student's readiness for particular objects, to provide formative assessment to improve student outcomes, and to provide summative assessment of the student's progress. In such applications, educational and, perhaps, cognitive theory can and should play an important role in the selection, the deployment, and the assessment of student work in data visualization.

Kopcha and Sullivan (2008) took an educational approach to a computer-based visualization module that was used to assist middle school children learn to perform integer arithmetic. The program was designed to provide visualization objects that had basic computational utility, but simultaneously provided content for understanding. One example is an animated number line that showed addition and subtraction as a series of jumps left or right. Their analysis showed a strong three-way interaction between student prior knowledge, student preferences for styles of representation, and amount of control over the information provided by the program. Kopcha and Sullivan's important result is that student prior knowledge is crucial to effective learning with the dynamic visualization objects that were studied. That is, students with high prior achievement performed better when they had control over their preferences of use and of presentation in the visualization. Students with low prior knowledge were unable to exploit their preferred modes and performed more poorly than when the program limited their choices. As the researchers used only a single program, it is not clear how general these results may be. Further investigation is clearly warranted.

The very existence of the *IEEE Transactions on Visualization and Computer Graphics* indicates that a powerful movement is in place. Our brief look at exemplars from research in the field suggest that considerable technical energy and expertise are at work in expanding the use of computer graphics not only in mathematics education, but also in the everyday work of people who use mathematics. While we recognize that a considerable amount of educational progress is likely to be made through the trial and error of the marketplace, it is nonetheless desirable that focussed educational research take place as this goes on. We simply cannot say with any certainty what kinds of dynamic visualization objects are likely to be beneficial for which students in their quest to learn which mathematical concepts.

## THE PUZZLE REVISITED

Earlier we raised a basic puzzle. Mathematics is by nature abstract, but visualization attempts to make mathematics concrete. What is gained by this operation? The research literature is tellingly divided on the issue. In one camp there are those who favour a semantic theory of visual processing. These researchers see visualization as a means for students to encode mathematical information in multiple ways to allow them to retrieve it later in various guises. Research in this area tends to look at the use of visualization to promote understanding. In contrast, we have seen syntactical theories that see the educational use of visualization as a means to assist the computational faculties of students by storing results, making relationships explicit, and so forth. As we have noted, the research is anything but decisive in adjudicating which of these theses best represents the cognitive situation in the use of visualization in mathematics education.

The apparent puzzle turns out to have a solution, at least in principle. If the goal of a mathematical activity is to relieve cognitive load on students by giving them an external reference, there are appropriate visualizations to be exploited. If the goal of a mathematical activity is to provide an alternative representation of a mathematical idea so that the student can provide justifications of the idea, then there may be appropriate visualizations to which the teacher can appeal. In either case, the purpose of making mathematics concrete is to work on or with the concrete object to highlight certain features of the mathematics, not to replace it completely.

The selection of educational strategies is contingent on the nature of the desired educational outcome, and the use of visualization is no different. There are no results in the research literature that suggest that visualization is a cure-all for mathematics education. We have seen clear cases where visualization is helpful in the application of mathematics, and clear cases where it is helpful in learning and justifying it. But we have also seen cases where visualization can be misleading and confusing to students. The source of the puzzle remains central to educational choices: visualization is a simplification and in some cases a falsification of mathematics. Its use requires serious reflection on the parts of both teachers and students.

## AREAS FOR FUTURE RESEARCH

Cognitive scientists will likely continue to explore the mechanisms by which visual information is processed. Perhaps when those mechanisms are better understood, cognitive models and empirical results will inform educational practice. Until that time, education will continue and visualization in mathematics education will be a domain worthy of further exploration in its own right.

First, we have seen that there are computational advantages to visualization. Pylyshyn (2003) has provided a worthy list of computational uses for visualization. To date, we are not aware of anyone who has systematically tested this list. While it provides a reasonable heuristic guide for practice, empirical research that develops clearer conditions for creating and utilizing computational visualization objects can and should provide sound recommendations.

Second, there is good reason to believe that students can use visualization to develop and to articulate their understanding of mathematical concepts. It is not clear when this is possible, and we are not aware of any fully articulated positions on mathematical meaning in visual contexts. Mathematics, like any academic discipline, has rhetorical standards of argumentation. An articulated statement of what sorts of argumentation are required by students at various stages of their mathematical development would be helpful in providing researchers with material to explore in terms of teaching, learning, and assessing the learning of mathematics.

Finally, visualization is no different from other means of educational instruction in that individual differences matter. Student prior achievement, student preferences, and student personal characteristics are not made to vanish through the use of visualization objects. Means of matching visual properties, interaction, and student achievement will need to be developed to guide appropriate use of visualization in instruction and in the assessment of student learning.

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# 7. VISUALIZATIONS AND VISUALIZATION IN SCIENCE EDUCATION

## INTRODUCTION

Visualization traditionally has been widely used and acknowledged as an important part of science education. Thanks to ongoing technological advancement it is becoming ever easier and less expensive to incorporate visualizations into science education practice. Not only static two-dimensional images, but also dynamic and even interactive visualizations have become possible, and prevalent, in contemporary science education.

Yet, before embracing this trend and encouraging a more extensive use of visualizations (both older forms and newer ones made possible through computers) science educators ought to reflect upon some key questions. The adoption of visualization in science education may not be capable of fulfilling our initial expectations, and may detract from the learning objectives we actually intend our students to reach.

In this chapter we pose several key questions about visualization in science education. First, we will frame the conversation by exploring what visualization is and how visualization occurs. Next, we will discuss why visualization is used in science education. With these points in mind we delve into how one may judge the pedagogical quality of a given visualization object. From there we will look into what is required of a student for interpreting visualizations. We investigate a series of examples that represent various types of visualization objects and explore the interpretive demands they make of students. We conclude by recommending a few general guidelines for science educators to consider when wanting to engage in pedagogically sound uses of visualization.

## WHAT IS VISUALIZATION?

The empirically grounded literature on the subject lacks a broadly accepted definition of visualization. In their survey of approximately 250 articles, books, and chapters on visualization dated between 1974 and 2009 Phillips, Norris, and Macnab (2010) were able to identify 28 explicit definitions of visualization, or closely related terms. They isolated three distinct concepts:

1. *Visualization Objects.* These are physical objects that are viewed and interpreted by a person for the purpose of understanding something other than the object itself... Other sensory data such as sound can be integral parts of these objects and the objects may appear on many media such as paper, computer screens, and slides.

*Stephen P. Norris (Ed.), Reading for Evidence and Interpreting Visualizations in Mathematics and Science Education, 123–145.*

2. *Introspective Visualization.* These are mental objects that a person makes that are believed to be similar to visualization objects. Introspective visualization is an imaginative construction of some possible visual experience.
3. *Interpretive Visualization.* This is an act of making meaning from a visualization object or an introspective visualization by interpreting information from the objects or introspections and by cognitively placing the interpretation within the person's existing network of beliefs, experiences, and understanding. (Phillips et al., 2010, p. 26)

This schema distinguishes between *physical objects*, *mental objects*, and the *cognitive process of interpreting* the physical or mental objects. Making a distinction between these three concepts of visualization in this manner provides a common vocabulary for discussing visualization and its use in science education.

Visualization objects of many different types are used in science education. Photographs, realistic and schematic diagrams, and mathematical graphs or charts have been employed in science education for a very long time. In recent decades computer generated graphics, animations, and interactive modules have come into existence, and been enthusiastically embraced by some educators. Later in this chapter we will explore examples of these visualization objects in detail.

In contrast to visualization objects, introspective visualization is less prevalent in practice and poorly researched in the scholarly literature. Perhaps this is because it is far harder for educators to guide what happens when they tell their class to imagine and begin to describe an image, than when they present their class with a visualization object. Whatever the cause, many educators and education researchers lack confidence in their knowledge of the pedagogical properties of mental objects relative to physical objects. It is clear that while similar in some ways visualization objects and introspective visualization are by no means equivalent. For instance "[Pylyshyn] (2003) notes that mental images do not preserve the realistic geometry of visual percepts, often allowing imaginary operations that would quickly be seen to be impossible in the visual image" (Phillips et al., 2010, p. 13) Although this difference may be a challenge in most educational contexts, introspective visualization is valuable in some advanced educational settings. For physical processes involving non-Euclidean geometry, such as motion at relativistic speeds, introspective visualization is used precisely because it transcends the limitations of traditional static two-dimensional visualization objects. Thus, the poor state of research on introspective visualization relative to visualization objects may indicate that pedagogically appropriate uses are going underutilized by science educators.

Interpretive visualization is very important in education because it speaks to what cognitive demands are placed upon students when they make sense of visualization objects. Phillips et al. (2010) point out that "in the absence of human cognitive engagement, visualization objects are merely sources of optical data" (p. 27). It is through interpretation that meaning is derived from the visualization objects. Our exploration of examples of visualization objects will focus on the demands placed on students when they engage in interpretive visualization.

## HOW DOES VISUALIZATION OCCUR?

Interpretive visualization goes beyond passively experiencing optical stimuli; the student plays an active role in visualization. “At some stage in the processing of raw data into a meaningful phenomenal experience, the contents of our thoughts enter into visualization” (Phillips et al., 2010, p. 35). How this occurs is an open question. Currently, there is no single cognitive theory that provides a completely satisfactory explanation of the mechanisms of visualization. There are, however, two basic theoretical perspectives that each provide a partial explanation of how visualization occurs. These are dual-coding theory and the visual imagery hypothesis. Additionally, the conjoint retention hypothesis is a third theoretical perspective formulated as a synthesis of these two basic theories.

Dual-coding theory (DCT) (Clark & Paivio, 1991; Paivio, 1986; Sadoski & Paivio, 2001) is based upon the assumption that “spatial and verbal stimuli are located in distinct memory codes that are accessible to one another” (Phillips et al., 2010, p. 37). Because visual and verbal information are coded and processed independently the interaction between these systems becomes significant. Under this hypothesis it is held that pedagogically appropriate uses of visual and verbal information together will reinforce each other, providing dual support to the student in learning and recalling the material. Thus DCT is applicable in situations where visualization objects are presented to students alongside verbal information.

The visual imagery hypothesis (VIH) (Johnson-Laird, 1998; Pylyshyn, 2003 Vekiri, 2002) holds that visual information can be more efficiently processed than verbal information, because it requires fewer cognitive transformations. The visual representation places less demand on the working memory of the students than sentential representations. VIH therefore is relevant in many problem solving contexts, where a visual representation may be more effective than a verbal aid.

These two cognitive theories are not necessarily incompatible with each other. Indeed, a third cognitive theory, the conjoint retention hypothesis (CRH) (Kulhavy, Stock, Peterson, Pridemore, & Klein, 1992) is firmly rooted in both. CRH is based upon the fundamental assumptions of *both* DCT and VIH and as such is applicable where these two theories would be considered to overlap.

In the context of science education, empirical studies allow us an insight into the effect of using visualization objects in specific educational contexts, and the DCT, VIH, and CRH perspectives help provide theoretical explanations of the findings. Yet a fully general theoretical perspective regarding the nature of visualization does not appear to be on the horizon. Phillips et al. (2010) caution that “educators and researchers should use the available results in contexts similar to those in which they were found, because we do not have theories adequate to the task of determining their generalizability to other situations” (p. 83). Heeding this advice, science educators should use caution when venturing far beyond the current literature in the use of visualization objects.

## WHY USE VISUALIZATION IN SCIENCE EDUCATION?

It may shed some light on this question to begin by asking, ‘Why visualize in science?’ Instinct may first suggest presenting realistic depiction of the world as the purpose of visualization. Yet, we quickly see that this is far from universally the case. Many of the visualizations used in science are highly schematic. And even more of them depict physical phenomena that are not directly observable, which makes it challenging to speak about how realistic they are. So, although a realistic depiction of the world may sometimes be the purpose of using a visualization object, it is only so in some cases. The purposes of visualization objects go far beyond this starting point.

Visualization has a long history of use in science. Phillips et al. (2010) recall how “[t]he development of both the new science of perspective and the printing press contributed to the emergence of scientific visualizations in various science disciplines” (p. 13). Scientists such as Galileo, Descartes, Newton, Maxwell, Einstein, Feynman, and many others have utilized it. Throughout the historical development of visualization in science, visualization expanded in scope through attempts to depict scientific phenomena that are further and further from being directly observable. Figure 7.1 (shown in a subsequent section) is an astrophotograph, an image from the boundary between what can and cannot be directly seen. Concurrently, the visualizations regularly take on more schematic forms culminating in the ultimate of mathematical abstraction in graphical depictions. Figures 7.2 and 7.3 depict such a shift from realistic to schematic styles in the study of optics. The first image is a rather realistic depiction of human vision by Descartes while the second is a highly schematic depiction of the splitting of a light beam with a prism by Newton.

So why do scientists bother engaging in visualization? The empirical nature of science implies that scientists are often engaging in making meaning of the data they have collected and in communicating with other scientists about it. Visualization can facilitate these processes by presenting the data in a more accessible manner than, say, a table of numbers or a verbal account.

Science educators, while recognizing the relevance of the proceeding use in science, must consider with greater weight the strictly *educational* purposes of visualization. The widely held viewpoint is that visualization is educationally useful; that it is a valuable aid to student learning. But what is the justification for holding this perspective? What exactly are the educational purposes visualization can effectively advance?

There are two sorts of purposes to which visualization can be put in education. The visualization can supplement another activity in order to assist understanding or the visualization can help solve problems. Using visualization to effectively attain a given educational goal likely means utilizing the visualization object for either, or possibly both, of these ends. As such science educators should remember that the purpose of an educational activity should influence how a visualization is chosen and used. Not all visualization objects are valuable, nor do they all work. Sometimes visualization may actually hinder the educational goal, in which case it ought not to be used.

## HOW IS THE QUALITY OF A VISUALIZATION OBJECT ASSESSED?

So far we have identified that the effective use of visualization in science education requires consideration of the context in which the visualization object will be used and the purpose that it is intended to fulfill in pursuit of the learning objective. How then is the quality of a visualization object to be assessed? How might one decide whether a given visualization object would effectively facilitate learning given the particulars of the situation? Unfortunately, in the absence of a comprehensive theory of visualization "research on visualization must proceed based on intuitions about picture usefulness rather than on informed judgement" (Phillips et al., 2010, p. 27). So too do science educators proceed on their intuition or by imitation of what the literature has demonstrated to be effective in similar situations.

The literature identifies five important features of visualizations. In relation to other fields of educational research there is a very meagre number of studies for a time span of almost three-quarters of a century. Which feature was emphasized at a particular time period shows major trends in visualization capabilities via the shifting emphasis of the research. These five features are "colour, realism, relevance, interactivity, and animation" (Phillips et al., 2010, p. 28). The features are not exhaustive. They are representative of the current body of research. Below we will provide a framework for these features. The intention of doing so is twofold: first, to provide a practical schema that science educators may use in evaluating the effectiveness of a given visualization object; second, through the presentation of a coherent and holistic viewpoint, to identify significant gaps in the extant literature to encourage a conversation about which features ought to be prioritized in future research. Sometimes we use the features themselves to refer to parts of the framework; at other times we discuss the features under different concepts.

### *Relevance*

Relevance, we argue, is the most pedagogically significant of all the identified features. By saying that the visualization object must be relevant we mean two things: first, that it must connect with the students' content knowledge and cognitive abilities and skills; second, that it needs to make a meaningful contribution towards the educational goals at hand. If a visualization object is not relevant to the student and the educational goals it is extremely difficult for it to positively contribute to learning as intended.

Part of determining the relevance of a visualization object involves reflecting on the background knowledge of the students in terms of the prior scientific knowledge and knowledge of any conventions (such as those in constructing scientific graphs) necessary to interpret the visualization object. Similarly, the visualization object must be appropriate to the cognitive abilities and skills of the students. For instance, if an image is overly complex through having many elements, a high level of detail in each element, or sophisticated relationships between elements, it will be challenging for the student to interpret the image as intended by the teacher. "What the learner brings to the task is extremely important. That is, the viewer's background knowledge and interpretive ability and skills play a major role in determining the teaching effectiveness of any visualization" (Phillips et al., 2010, p. 32).

Even if the visualization object is appropriate to the students' content knowledge and cognitive abilities and skills, it may not actually serve the educational goals. The image must aid the student in reaching understanding of the learning objective. Ultimately, if the visualization object fails to contribute to, or even distracts from, the educational purpose at hand, it ought not to be included in the lesson.

The discussion of all features that follow ought to be considered in relationship to this point. The use of colour, realism, animation, or interactivity do not have any inherent educational value but rather derive value in accordance with how effectively they serve the students in reaching the learning objectives.

### *Appeal*

With regards to educational value, appeal could be thought of as a pseudo-feature of visualization objects. As mentioned earlier, the rise of the computer age has opened new vistas for visualization, making possible the creation of objects that were undreamt of a few decades ago. These vivid images, flashy animations, and manipulable applets are appealing and capture student attention. If appeal is created in service of the educational goals, perhaps by inspiring students to pursue the learning objective with more effort, it is beneficial. However, appeal alone does not provide sufficient grounds to justify designing a visualization object in a particular manner. "If the only effect is increased interest with no concomitant effect on understanding or achievement, then other factors such as time, efficiency, and expense can play a larger role in decisions about the use of [a particular element]" (Phillips et al., 2010, p. 30). A visualization object that is appealing yet fails to relevantly serve the task at hand is thus of scant educational value.

### *Realism*

The concept of realism represents how true to the physical world the visualization object is. All visual properties impact how realistic the image is, although the two most emphasized in the literature are colour and texture. The value that realism holds is entirely dependent on the educational context and purpose under consideration. For instance, discussing a rare animal most students have not seen before may suggest presenting a photograph or video recording of the animal. Meanwhile, a schematic drawing may better facilitate learning the anatomy of the human heart as details in overly realistic depictions might distract the students from their primary educational goal. Empirical, rather than philosophical, grounds are the correct way to determine the appropriate level of realism.

However, in some cases realism as conceptualized so far is not a relevant feature of the visualization object. Recall that many images used in science education do not depict objects that can be directly seen. Yet it seems possible, and here we speculate, to extend our concept of realism to become something akin to the concept of analogy. Consider how visualization objects used in science education are representations of physical phenomena. There are analogous elements in the image that map onto elements in world. When it is possible to directly observe the phenomena so depicted, one can intuitively speak about the realism of the image, by which one is speaking about how directly correspondent the mapping is, or how little it abstracts. If we think of realism in this expanded manner, one may still speak about the degree of abstraction even when the phenomena are not directly observable. For instance, when considering the concept of diffusion, a graphical representation of how the solute concentration changes over time on each side of the permeable barrier is more abstract than a series of visual images that illustrate the same concept. Thus one could consider the graph to be more abstract, or less realistic, than the series of images. But, the degree of abstraction of a visualization object has no inherent value. The judgement of appropriateness can take place only when the context, including the students' knowledge, and purpose of the educational task are known.

### *Visual Properties*

Visual properties are the basic components of a visualization object; they are the elements of which the image is composed. Yet this is where the literature is most lacking in terms of coherence and completeness. Colour, as a feature of visualization objects, is almost universally studied in conjunction with the texture of the image. Texture refers to those elements of the image that evoke an impression of what it might feel like if the object depicted were to be touched. Think of variations in the thickness, the crispness, and the patterning of lines, or of the patterns of repeating details that fill an area. Colour and texture ought to be considered as two separate dimensions. An image may be black and white (or grayscale), composed of a finite number of discrete colours, or in full colour. For any of these cases the texture could be akin to a crisp line drawing, a smoothly shaded drawing, or a fully detailed photograph. The current state of the literature does not explore in sufficient breadth or depth the impact that colour or texture have on learning with visualization objects.

Spatial properties are not explicitly acknowledged as a feature of visualization objects by Phillips et al. (2010), although they implicitly recognize them in their discussions of images in sundry parts of the book, most obviously in terms of the spatial proximity of elements of an image. Other spatial relationships between elements include their relative scale, their shapes, and their arrangements or groupings.

We suggest that recognizing colour, texture, and space as visual properties in this manner opens up new possibilities for research into visualization in science education. It seems plausible that a survey of how visual properties are addressed in the fields of design and the fine arts would provide a more exhaustive list of visual properties and an understanding of their interrelationships. With such a conceptual framework in place it would then be much more straightforward for education researchers to empirically explore the pedagogical significance of these features of visualization objects.

### *Animation and Interactivity*

The rise of powerful personal computers created enormous opportunities for visualization in science education. Technological advance has made it economical to produce and use animated or interactive visualization objects. Harkening back to our discussion of appeal, using these visualization objects merely because they are new and novel and therefore appealing is not a pedagogically sound justification. They ought to be used in science education only if they serve the learning objectives.

The primary pedagogical justification for using animated visualization objects is that they "are able to show time-domain changes in a way that static diagrams and drawings cannot" (Phillips et al., 2010, p. 34). While this places unique interpretive demands upon students, in most other regards they share features with static images.

Interactive visualization objects, however, have been shown by the research "to facilitate greater levels of interpretive visualization than do other types of visualization objects" (Phillips et al., 2010, p. 32). That the students can control and manipulate the object allows them to test their own hypotheses. This means that a student's background knowledge can change while engaging with the visualization object, promoting an iterative process between interpretive visualization and knowledge formation as the student tests out newly formed hypotheses.

## WHAT DEMANDS DOES INTERPRETATIVE VISUALIZATION MAKE OF STUDENTS?

Questioning what prior knowledge and intellectual abilities and skills might be integral to using a given visualization object is important in determining its quality with regards to an educational context. Visualization places demands upon the students. The educator must reflect on what the image requires of the student to be used effectively in the learning process. In this sense the cost of using a visualization object goes beyond the time and effort required of the educator to create or access it. It also involves the effort required by the student to use the object, and the efforts required of the educator to support the students' success in this endeavour. The educational benefit to be derived from a visualization object needs to be weighed in relation to these costs.

As previously described, interpretive visualization is the act of making meaning of a visualization object. Through interpretive visualization the student strives to gain a clear notion of the physical phenomena that the visualization object depicts. This effort involves both interpreting meaning from the image and contextualizing the meaning within the student's prior knowledge. Accomplishing this end requires a student to do and know certain things. One starting place for this process is the visualization object itself. “The use of visualizations in any mode or style involves not only an awareness of the properties of the object itself, but also a familiarity with the forms of symbolization that appear in the object as proxies for reality” (Phillips et al., 2010, p. 27). The other starting place is with the necessary background scientific knowledge. The student may possess this knowledge from prior courses and life experience, or the educator may introduce it alongside the visualization object.

Regardless of the starting point, the crux of the interpretive visualization process is the mapping of the properties of the visualization object to the properties of the physical phenomena they represent. Arguably this is the most important element in this process of interpretive visualization. It is clear on the face of it that if no connection is made between the image and reality no educationally useful meaning has been interpreted from the image. “It seems clear that even a trivial interpretation of visualization objects requires that the student utilize attributional and inferential strategies. This is so because, in the absence of human cognitive engagement, visualization objects are merely sources of optical data” (Phillips et al., 2010, p. 27). The better students’ understanding of the mapping, the deeper the meaning they are able to derive, and the more educationally useful the exercise. Although effectively interpreting the visualization object requires knowledge of the conventions used in the image and certain scientific background knowledge, neither of these things are useful in making meaning of the image unless some mapping is in place.

In the following two subsections we survey some of the different kinds of mappings that a student may engage during interpretive visualization. In doing so we will draw upon the examples of visualization objects used later in this chapter.

### *Interpreting Spatial Relationships*

Arguably the most fundamental feature of visualization objects with regards to interpretive visualization is the spatial relationship between elements. This is so because the vast majority of visualization objects are presented on a two-dimensional plane, whether on paper, computer monitors, projector screens, or televisions. Using such media, the elements of the visualization object necessarily hold spatial relationships to one another. Perhaps the most prominent of these is physical proximity, but the relative scale, shape, and arrangements or groupings of elements may also hold significance that must be interpreted.

The spatial proximity of elements may be interpreted in a variety of ways; they may be mapped onto different aspects of the physical world. As we will come to see they may represent spatial relationships, as in Figure 7.3 where the distance between the lines DE and *de* in the diagram represents a distance of twelve feet. They may represent temporal relationships, separation in time, as along the horizontal axis of Figure 7.4, or perhaps some other quantitative physical relationship such as a number of hare or lynx pelts as is seen along the vertical axis of Figure 7.4. The relationship may be entirely conceptual, such as is found in a concept map of the geological cycle that illustrates the processes that cause transformation between igneous, sedimentary, and metamorphic rocks. And yet, the physical relationship may be entirely arbitrary. In this case interpreting the visualization object consists of recognizing that there is no meaning contained in the positioning of one graph relative to another in Figure 7.6.

In a related manner the relative scale of two elements may convey a meaningful relationship. Consider for example how on maps two dots representing urban centers may carry information both about their distance apart and population levels through their spatial separation and their relative sizes, respectively. Likewise, the meaning behind relative shape and the arrangements or groupings of elements may need to be interpreted.

Recognizing that there are multiple ways of mapping the spatial relationships in a visualization object onto the relationships of the elements in reality seems to be one of the most basic tools required in interpretive visualization. If this principle is not understood by the student it may rapidly lead to intractability in interpreting a visualization object through either missing the meaning of a vital relationship or obsessing over an arbitrary arrangement.

### *Interpreting Non-Spatial Relationships*

Animations introduce temporal relationships between the elements of the visualization object. These are more complex than static visualization objects, because both spatial and temporal relationships must be considered in interpretive visualization. The temporal relationship often represents a scaled temporal relationship. In the animation represented by the static Figure 7.5 the animation proceeds from 1950 to 2010. Displayed at about a second a year the animation thus portrays global changes that took place over 60 years in about a minute. However, in some animations a temporal relationship represents a spatial relationship. An example of this is an Magnetic Resonance Image (MRI) animation, wherein each image represents a cross section of a person's brain, for example, and subsequent images represent a progression through the person's head along the third spatial axis.

Other visualization properties are also able to convey meaningful information about the relationships between elements. The relative intensity or hue of colour are obvious examples; consider the ubiquitous use of red and blue to represent hot and cold temperatures.

This variety suggests a large number of possibilities that students must consider when engaging in interpretive visualization. When they consider elements of a visualization object they must evaluate whether or not the differences in the visual properties of the elements encode meaningful information. If they determine that the differences are meaningful they must identify the appropriate mapping to the physical phenomena. One of the most important things science educators must teach their students when using visualization objects is that there are mapping conventions, such as the set of standard conventions used in scientific graphs. The student must recognize that a given relationship between elements in a visualization object may be interpreted in one of many different ways, or may actually not represent any meaningful relationship.

## EXAMPLES OF COMMON VISUALIZATION OBJECT TYPES USED IN SCIENCE EDUCATION

Our goal in this section is to provide some concrete examples of visualization objects used in science education. We will explore their interpretive demands and seek insight into their pedagogically appropriate use. We introduce several different types of images to provide a broad, though non-exhaustive, representation of visualization objects. We analyze each image according to the outline in the next paragraph. Aspects that are marginally relevant or irrelevant are omitted from our analysis.

In recognition that relevance is the most pedagogically important feature of a visualization object we will begin our discussions with it. Next we will speak to the interpretive demands placed on students while they seek to make meaning of visualization objects. The properties of the visualization object and the significance of the relationships between its elements will be examined and interpreted. We may, depending on the object, focus on spatial, colour, texture, or temporal relationships. When appropriate we will provide a discussion with regards to interactive visualization objects. Finally, we will comment on the realism, the degree of abstraction, and on the analogy between the visualization object and phenomenon it depicts. Throughout this discussion we will address the kinds of pedagogical points it may be useful for a science educator to reflect upon in using the visualization object.

The first four examples we present are signposts along the spectrum of realism. The first is an astrophotograph taken by the Hubble Space Telescope. Next is a pair of diagrams of optical phenomena; an elaborately realistic diagram by Descartes and a much more schematic diagram by Newton. Fourth, we look at a graphical depiction of population dynamics through the classic example of the hare and lynx. The last two images represent screen shots taken of applets from the King’s Center for Visualization in Science. The first is from an animation of Surface Air Temperature change over six decades. The other is an interactive visualization object that depicts the mathematical properties of West Nile Virus transmission in mosquitoes and birds.

### *The Spectrum of Realism*

Earlier we addressed how one may view realism as how true the visualization object is to the physical world. The visual properties of the image’s spatial elements and relationships, colour, and textures determine the degree of realism. We extended this concept so as to be applicable to non-visual phenomena by framing realism as the degree of abstraction of the analogy between the visualization object and the phenomenon it depicts. Ultimately, we observed that the degree of realism of a visualization object has no intrinsic pedagogical value. It is worth being considered only with regards to how well the degree of realism serves the student in attaining the educational goal. Some visualization objects are highly realistic and serve pedagogically sound purposes by being so, yet "[m]any of these objects are deliberately non-realistic because their usefulness is a function of their logical form, not merely their verisimilitude to nature" (Phillips et al., 2010, p. 18).

This section has been structured into three subsections: *Photographic Images*, *Realistic and Schematic Diagrams*, and *Scientific Graphs*. In the first we discuss photographs and astrophotographs— images that have high fidelity to the optical sensation one would experience in seeing the original object. Next we explore two examples of visualization objects that show different degrees of abstraction. Lastly, we examine a scientific graph, where the degree of abstraction from the physical phenomena it depicts is high.

*Photographic images*. Photographs seek to reproduce the sensory experience of directly seeing the objects they depict. But how is a science educator to determine if such a high degree of visual fidelity is pedagogically appropriate to the context? Consider a photograph of a horse: "the illustration may serve only as a reminder of a previous visual experience. If so, it is difficult to see how the pictorial reminder could be superior to any other reminder, including the word 'horse' (Phillips et al., 2010, p. 7). To justify the cost of making and using a visualization object a more substantial reason is necessary. For instance, a diagram of a horse that instead focuses the students' attention on an aspect of a horse or detail in its behaviour that is relevant to the educational goal at hand could be more pedagogically useful than a verbal description of the trait. Or consider, instead of a horse, an okapi. This is a striking mammal that looks as if it possesses a giraffe's head, a horse's body, and a zebra's legs. Depending on the prior knowledge of the students and their cognitive abilities and skills, a photo may not merely be appropriate, but necessary in enabling the students to make meaning of such a description.

As addressed earlier, many of the phenomena dealt with in science, and by extension science education, are non-visual. However, the boundary between visual and non-visual phenomena is not clear-cut. The development of devices such as optical microscopes and telescopes has extended human sensing beyond its original limitations to the very small and the very distant. The fields of photomicrography and astrophotography capture the optical data from these devices thus enabling the creation of visualization objects that depict phenomena that could never be seen directly with the naked eye. Yet these images are talked about as if they had the same fidelity to reality that a photograph of a horse or okapi does. In both circumstances it is straightforward to infer that if our eyes were superior in some way, able to discriminate smaller resolutions or detect fainter objects, that we would see precisely what is depicted in the photograph.

As a particular example of an astrophotograph we present Figure 7.1, an image of the Sombrero Galaxy that is also known by its Messier object number as M104. The Hubble Space Telescope took this particular image, which is made available to

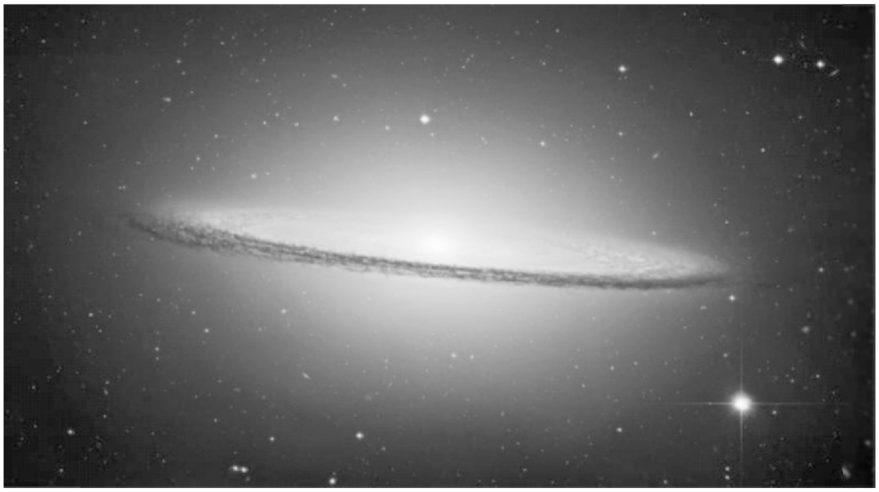


*Figure 7.1. Astrophotograph taken by the Hubble Space Telescope of the Sombrero Galaxy (M104).*

the public by NASA and the Space Telescope Science Institute (STScI). It is presented here in black and white while the source image is available online in colour. The primary impact of presenting the image in full colour would be to increase its appeal with little added pedagogical value because colour is not only determined by the properties of the galaxy but also by the means of detection and representation.

As emphasized previously, judging the quality of a visualization object must be done in relation to the educational objectives and context. The appeal of the image may be used to inspire students about scientific discoveries and motivate them in their course work. Figure 7.1 may be used to teach students about "how a galaxy's orientation affects its appearance" (NASA, 2004, p. 3). NASA (2004) explains by saying "[a] galaxy, when viewed from above, appears round. A galaxy viewed from the side, or edge-on, looks like a flat pancake" (p. 2). Figure 7.1 contains many visual details, and separating those details that are relevant or irrelevant to the structure of the galaxy would be a complex and demanding task. So that this complexity does not distract students from the learning objective, NASA (2004) suggests that students acquire prior knowledge about the structure of spiral galaxies, specifically about the bulge, the disk, the halo, and the spiral arms. Similarly, students should be able to recognize foreground stars in the image that are not part of the Sombrero Galaxy.

The Sombrero Galaxy is an unbarred spiral galaxy in the constellation Virgo, 28 million light years away, that is oriented almost edge on towards the Earth. It is not visible to the naked eye but its outline and basic structure are observable with an amateur backyard telescope. Greater detail can be seen in Figure 7.1:

> The central bulge, for example, can be seen extending above and below the galaxy's flat disk. This view also shows that the disks of galaxies are thin.

> Dust in the galaxy's wide, flat disk blocks out light from Sombrero, appearing like a shadow against the bright bulge of stars. (NASA, 2004, p. 2)

Possessing the required prior knowledge of spiral galaxy structures, students should easily interpret this textual description. Making meaning of the image in relation to this text is more challenging. Deriving meaning from the image requires that students interpret the spatial separation and relationships of its elements as well as their relative brightness. Using the text they must construct the analogy between the elements in the image and the physical structures that make up the real galaxy, situated far away in space and extending 50 thousand light years across. Recognizing the bright central sphere as the central bulge and the highly textured surface of the flat ellipse as the galactic disk requires the students to consider multiple components of the image as part of a unified whole.

Achieving the learning objective requires students to recognize familiar structures in an unfamiliar orientation and of learning how that orientation affects the galaxy's appearance. Figure 7.1 is one component of the lesson, along with textual description and oral instruction that assists students in reaching the learning objective.

*Realistic and schematic diagrams.* Diagrams deliberately depart from a literal representation of reality. They abstract specific elements of the object or phenomenon depicted to more effectively emphasize particular characteristics. Yet, the object or phenomenon depicted remains fairly recognizable. Scientists and science educators are not merely concerned with what the world looks like but also how it operates. Diagrams do not always serve to exactly depict the world, such as photographs do, but may instead serve "as devices to help us conceive how [the world] might work" (Baigre, 1996, p. 116). They do so by emphasizing certain features of the world, in a way that departs from literal depictions, that are important to the scientific explanation at hand. As such this type of visualization object is particularly relevant to, and prevalent in, science education.

Descartes and Newton are two scientists who used numerous illustrations in their scientific work. While most of their scientific theories have long since been replaced, many of their discoveries and achievements are still referenced in contemporary science education. This is certainly the case in optics where their works, and occasionally their visualization objects, are still encountered. Figure 7.2 is typical of Descartes' diagrams in that, despite departures to better illustrate how human vision works, it retains many realistic elements that act to situate the phenomenon of vision. Figure 7.3 demonstrates Newton's style of schematic diagrams wherein "Newton stripped away much of Descartes' symbolic and stylistic material, leaving a more idealized visual aid for the reader to focus more on the phenomena being described and less on its cosmological context" (Phillips et al., 2010, p. 15).

However, as we have already argued, we cannot judge the quality of a visualization object solely on its degree of realism. We must keep in mind that the original audiences and purposes of these two images were very different. Descartes' illustrations were meant to convince other people, lay and scientist, about how the world worked—to aid them in concept change. Thus he followed

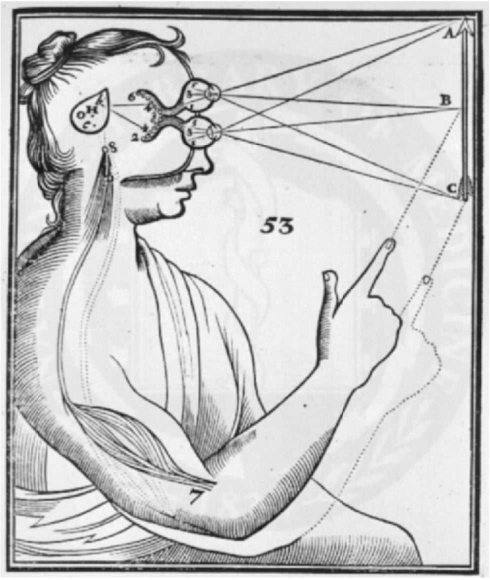


*Figure 7.2. Realistic diagram drawn by Descartes depicting the optics of human vision.*

certain widespread eighteenth-century conventions for scientific diagrams, such as that “the eye is replaced with a full-sized human figure” (Baigre, 1996, p. 93). Newton’s illustrations were meant for scientists as an aid to figure out how to reproduce his experiments—a form of problem solving. Newton established many of his own conventions, which were described in detail in the accompanying text. As Newton’s conventions are the direct ancestors of ours, his image may seem less odd despite being much less realistic than Descartes’ image. Baigrie (1996) explains that “in the shadow of Newton’s *Principia*, Descartes’ pictorial devices seemed a lot less like science and more like works of art–symbolic renditions of natural things that bore little connection with reality” (p. 129).

It is fairly straightforward to recognize many of the elements of Figure 7.2. While “Descartes takes liberties with the geometry of the face...the diagram retains many realistic features nonetheless” (Phillips et al., 2010, p. 14). Yet, one of the significant interpretative demands of this image is determining which elements are important to the phenomenon of human vision and which are irrelevant. This necessitates the accompaniment of a textual description or oral instruction. Otherwise, “it is not obvious which features of Descartes’ illustration are relevant to the understandings of what. Are the eyes important? Does the gender of the subject matter? What are those lines piercing her eyes? What is she pointing at?” (Phillips et al., 2010, p. 27). Recognizing the important elements and their relationship to each other, both in the image and in reality, involves many judgement calls on the part of the student. For instance, the gender of the subject must be recognized as irrelevant although the lines piercing her eyes are vital because they trace the paths of light rays from the arrow to her eyes.

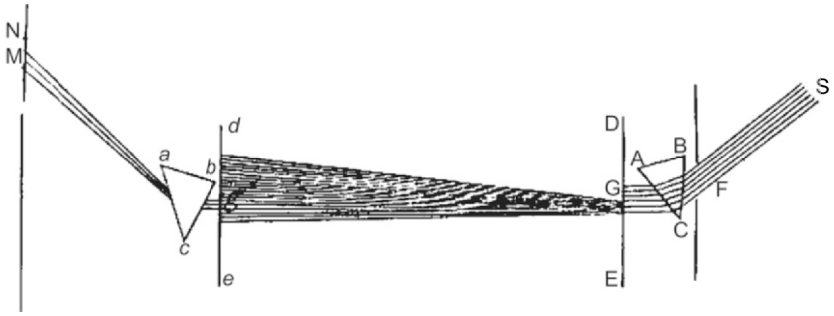


*Figure 7.3. Schematic diagram drawn by Newton depicting the optics of the separation of the light spectrum with a prism.*

Figure 7.3 is an entirely schematic diagram. There is a very precise correspondence between its elements and reality, specifically to an experiment showing that the colour of a light ray dictates how refrangible it is. In Newton's *Opticks* the experiment is first described in detail. Then the illustration and its correspondence to the experiment are carefully outlined. For instance, the distance between DE and *de* in the diagram represents a distance of twelve feet in the original experimental setup. Actions from the experiment can be mentally simulated using the diagram: "by turning the Prism ABC slowly to and fro about its Axis, this Image will be made to move up and down the Board *de*" (Newton, 1730, p. 46). This experiment can be repeated with science students to explore the refraction, among other behaviours, of light.

The most challenging interpretive demands made by Figure 7.3 relate to its appearing less accessible, or more remote, than Figure 7.2 from the day-to-day experience of students. Although mapping the analogy between the illustration and reality may be less direct and more demanding in Figure 7.3, there are significantly fewer distractions than there are in Descartes' image. By minimizing the non-scientific content of the image Newton succeeded in eliminating distractions that make interpretation more cognitively demanding.

*Scientific graphs.* Over the course of history scientists have increasingly dealt with aspects of reality that are removed from visual experience. They have struggled with finding a vocabulary to describe these unobservables. "This problem of language was partially resolved through scientists' increasing ease in using mathematical expressions to describe and discuss the non-visualizable" (Phillips et al., 2010, p. 15). Thus, mathematics is often referred to as the language of science. In turn there was the challenge of visualizing the mathematical expressions, addressed through the use of scientific graphs. At its most basic "a simple 2D graph is a geometrical representation of the relationship between two variables" (Phillips et al., 2010, p. 4). More complex scientific graphs may be 3D, incorporate the use of colour, or involve other visual properties to depict the relationship between larger numbers of variables. Since scientific graphs represent a high degree of abstraction from reality, it may be challenging to connect the elements of the graph to the physical phenomena they represent. A student is dealing with a double transformation from the original concept—they must interpret a visual depiction of a mathematical representation of the physical phenomena.

While "students have been sketching graphs since Descartes introduced them in the seventeenth century" (Phillips et al., 2010, p. 4) the literature contains little research on the use of graphs as visualization objects and the studies that exist tend to focus on mathematics education contexts. Therefore, our analysis in this section is more tentative than in other sections of this chapter.

For the past half century, Figure 7.4 has been an extremely widely used graph for introducing the concept of population dynamics, and specifically the phenomenon of predator-prey population cycles, to senior high school and university students. The graph is typically used to support learning objectives such as defining populations, identifying changes in population levels over time, and understanding causal relationships between the population levels of different species. This visualization object simultaneously depicts variations over time in population level for the Canada lynx and snowshoe hare based on real world data collected by trappers of the Hudson Bay Company (MacLulich, 1937). The Canada lynx almost exclusively eats snowshoe hare, and in turn forms the snowshoe hare's primary predator resulting in their population levels being tightly linked.

Perhaps the most challenging interpretive demand made by scientific graphs is knowing and applying a large number of conventions when making meaning of them. Conventions are front-end loaded, in that after a student has learned them they must be recalled and applied to later graphs. This increased challenge in making meaning of individual graphs initially is mitigated in the long run. Interpreting many graphs of the same type by applying standard conventions makes interpretation easier with subsequent graphs.

One convention a student must apply in interpreting Figure 7.4 is the standard placement of the independent variable, in this case the passage of time, on the horizontal axis, and the dependent variables, population levels of hare and lynx, on the vertical axis. Recognizing that the graph is oriented this way is necessary to make sense of accompanying verbal or textual descriptions of "population peaks" and "valleys". Another convention is the use of arbitrary differences in the texture, or colour, of lines to simultaneously display multiple dependent relationships. A legend is used to state the correspondence between the texture, or colour, and the variable. Such a graph is more complex and more cognitively demanding than one with only a single dependent variable. If the student does not know these conventions, it may be impossible to derive the intended meaning.

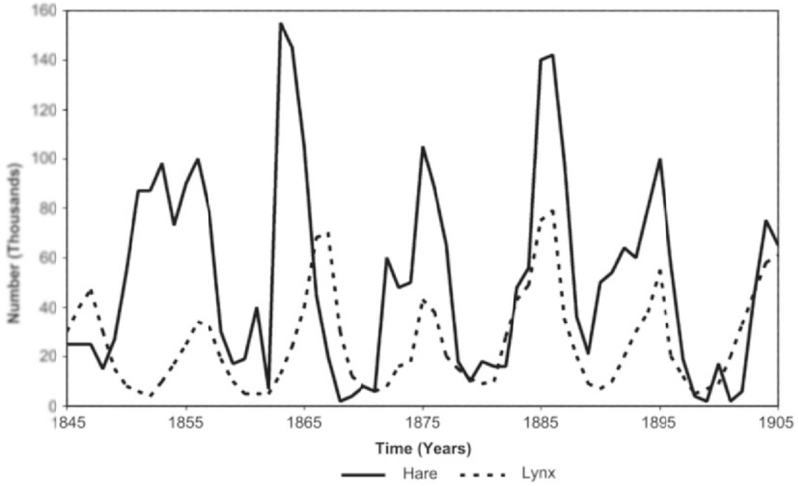


*Figure 7.4. Graphical representation of the population cycles of hare and lynx populations as redrawn from the original work by MacLulich (1937).*

### *Animations*

Animations have been used in education for many decades as narrated films or drawings of scientific phenomena. In the past two decades computer-generated animations have played an increasing role in visualization in science education. From their review of the literature Phillips et al. (2010) concluded: “animation should be used only when the knowledge to be gained is related to movement or can be better understood if a 3D visual is shown (for example, trajectory of movement, chemical bonds, layers of epidermis on a cadaver)” (p. 34). Animations are inherently more complex and place higher demands on memory than static visualization objects do, and it is inadvisable to increase the demands unless it is pedagogically necessary. Furthermore, to minimize this extra cognitive load animations “should be short, simple, and obvious in terms of what is being demonstrated” (Phillips et al., 2010, p. 34). Lastly, animations are most effective when used in parallel with narration, as suggested by the dual-coding theory, rather than being presented merely as a visual experience.

The static Figure 7.5 is a single frame from an animation created by the King’s Centre for Visualization in Science (KCVS). It is part of the Visualizing Global Climate Change Applet, and is intended for students “to compare annual surface temperatures and other climate variables at different locations on the earth for the period 1950 – 2100” (KCVS, n.d.). The educational purpose of the animation is “to help learners visualize and understand the underlying science of climate change” (KCVS, n.d.). In this animation each frame is a map of the world that is coloured according to the average surface air temperature. Colours shade from red for warm regions through white to blue for cool regions. As the animation runs, changes in surface air temperature are depicted by changes in the colouring of regions on the world map.

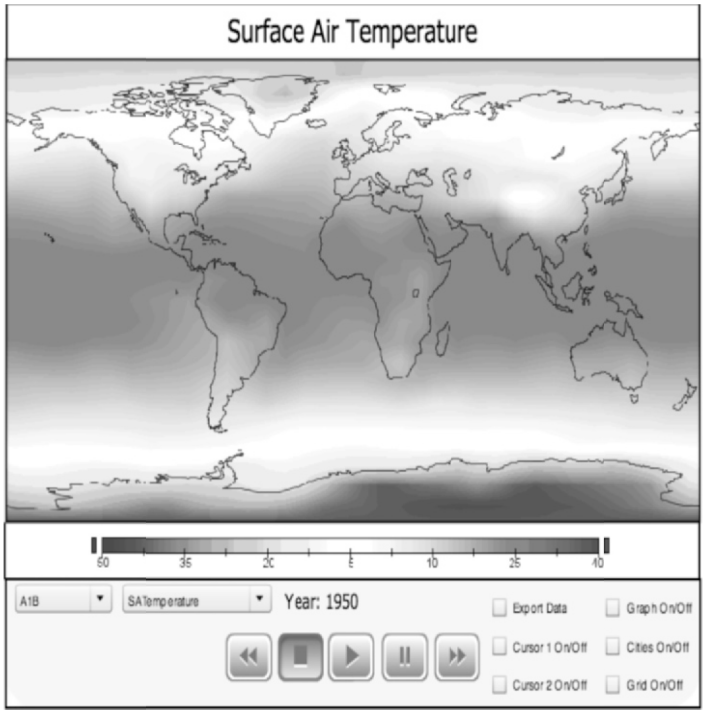


*Figure 7.5. Screenshot of KCVS's animation on Visualizing Global Climate Change.*

During interpretation "many of the same issues that have been raised for static objects transfer to animations" (Phillips et al., 2010, p. 34). As such it is recommended that animations should be as simple as possible while meeting the education goal, so as not to confuse or distract students. As part of making meaning from Figure 7.5's animation a student must meet all the same demands related to recognizing continents and countries and interpreting spatial relationships required by a map. What is distinct is that the student is constantly re-evaluating the derived meaning as the image changes over time. The students must track changes as the image progresses, comparing what they see with what they recall from earlier frames and making meaning out of the changes. The demands on memory are much greater than with static images. As such, the literature recommends that students be given the option to control the pace of animations, to pause, slow down, or replay them, so as to reduce this cognitive demand.

### *Interactive Visualization Object*

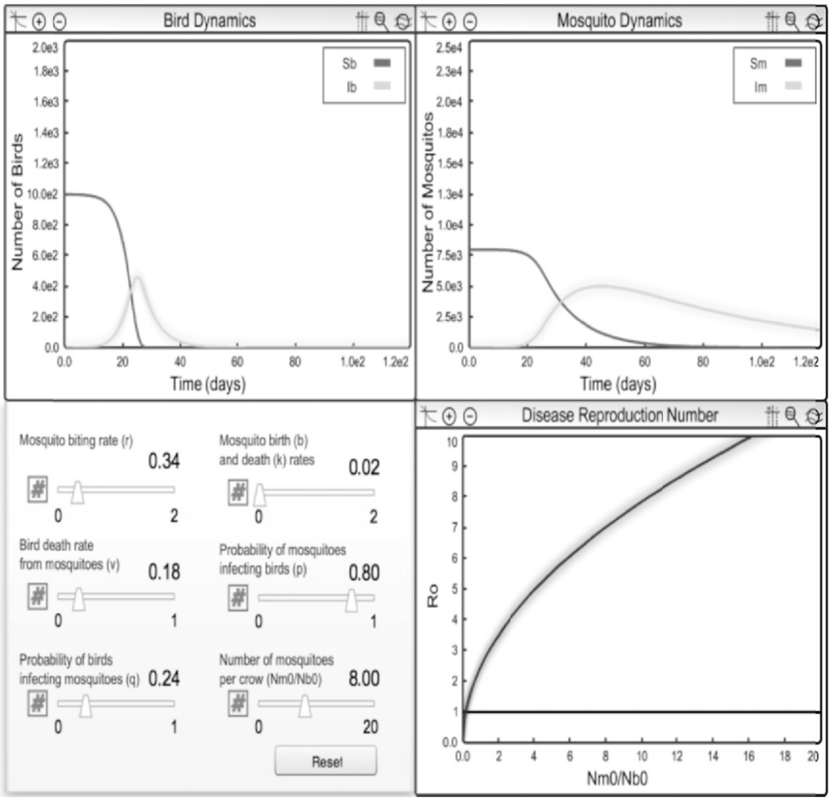
We've already mentioned that interactive visualization objects can assist in reaching deeper understanding than non-interactive visualizations. According to the literature they are "uniquely beneficial because the learner can control and manipulate parts of the presentation, can test hypotheses, and can witness consequences through programme feedback" (Phillips et al., 2010, p. 32). This element of student control is at the pedagogical heart of why interactive visualization objects seem to be so effective. Yet, at the same time, pragmatic considerations about "the possibility of combining language and a dynamic visual display while allowing the user to control speed and other presentational factors underwrite much of the current enthusiasm for computer-based visualization" (Phillips et al., 2010, p. 81). For these, among other reasons, the last two decades have seen a great focus on interactive visualization objects in the research literature.

Figure 7.6 is a screen shot from the interactive West Nile Virus: Mathematical Modeling to Understand and Control a Disease applet hosted by KCVS. The learning objectives behind the applet are "to show students how mathematical models can be used to furnish useful insights into important problems" (KCVS, n.d., para. 1) and specifically to learn "how the spread of the West Nile virus can be understood by modeling the interaction between mosquitoes and crows" (KCVS, n.d., para. 2). The student interfaces with the applet by setting the value of six parameters through the use of the sliding bars in the lower left corner of the image. The figure contains three separate scientific graphs that show the resulting relationships between variables. The graphs change in response to student input.

Like animations, interactive objects are more complex, and thus more cognitively demanding, than static images. Also, the kinds of interpretive demands presented by static images remain applicable. The West Nile Virus (WNV) applet response to student input is displayed as a set of three scientific graphs. Two of the scientific graphs in Figure 7.6, Bird Dynamics and Mosquito Dynamics, are very similar to Figure 7.4 in that they are also graphs of population dynamics and thus place many of the same interpretive demands on the students.

The first challenge a student faces in interpreting an interactive visualization object is to understand how the interface works. In many cases a tutorial or demonstration is used to provide the students with this necessary knowledge before they begin to interpret the educational content of the object. Careful consideration must be put into designing the interface, so that the cost of learning how to use the system does not outweigh the educational benefit it provides. The sliding bars in Figure 7.6's applet are an appropriate interface for high school science students to use.

A second cognitive demand made by these kinds of objects is on student memory. In a single session a student may test multiple hypotheses through trying many different manipulations of the object. The literature raises "the theoretical concern that some of the benefit derived from a computer-based visualization object is lost if the user does not have access to a robust system that allows for the review and retrieval of previous results" (Phillips et al., 2010, p. 80). Thus, many interactive visualization objects possess the ability to record and export the results of the activities the student engaged in, thus reducing the cognitive demands on recall. Yet, even if the program can record the results of simulations, it is equally important for a student to recall why they engaged in that manipulation to begin with. Thus, in many cases, such as with the WNV applet, it is beneficial for the students to keep logbooks similar to ones they would use when conducting an experiment.



Mosquito biting rate (r) 0.34 (0–2)

Mosquito birth (b) and death (k) rates 0.02 (0–2)

Bird death rate from mosquitoes (v) 0.18 (0–1)

Probability of mosquitoes infecting birds (p) 0.80 (0–1)

Probability of birds infecting mosquitoes (q) 0.24 (0–1)

Number of mosquitoes per crow (Nm0/Nb0) 8.00 (0–20)

*Figure 7.6. Screenshot of interactive applet on the West Nile Virus: Mathematical modeling to understand and control a disease.*

## CONCLUSION

We began this chapter with an observation and a caution. It is widely noted that visualization has an important and beneficial role in science education. If used appropriately visualization is valuable for such purposes as aiding in forming new understandings or as a tool in problem solving. Yet, we cautioned that science educators ought to be critical in their use of visualization so as not to embrace it as a panacea. By learning about what visualization is, how it occurs, and its limitations, science educators become better able to identify when using it is appropriate or not, and thus better able to make informed choices in their teaching practice.

Perhaps the most frequent visualization danger in science education comes from being captivated by an image and afterward seeking a reason to include it in a science lesson. Without a doubt, many visualization objects are highly appealing. Yet, in their review of the research literature Phillips et al. (2010) made the observation that "the usefulness of visualization in science seems to have much to do with a match between the activity and the desired outcome" (p. 74). This observation seems to us to be the key point science educators ought to be considering. We present the following as a list of questions as one way for educators to reflect on this point:

– What learning objective is being taught?
– Is it possible for this learning objective to be achieved through the use of a visualization object?
– What concomitant benefits, such as increased student motivation, would be gained through using a visualization object?
– What time, effort, and resources on the part of the instructor are required to prepare for the use of the visualization object?
– What interpretive demands, in terms of prior knowledge and intellectual abilities and skills, does the visualization object place on the students? Are the students able to meet these demands?
– Do the benefits of using a visualization object to meet the learning objective(s) outweigh the associated cost of doing so?

Wherever possible, answers to these questions should be guided by literature informed by research. Caution must be employed in generalizing beyond the contexts in which the results were found. Yet, where the literature is silent, science educators must continue to rely on their informed instincts about visualization in science education in making these judgments.

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# 8. CURRICULUM DEVELOPMENT TO PROMOTE VISUALIZATION AND MATHEMATICAL REASONING: RADICALS

## INTRODUCTION

Imagine $\sqrt{2}$. What first comes to mind? For you is $\sqrt{2}$ a number? Is it a radical? Is it a measure? Is it the length of the diagonal in a unit square? Is it the length of the hypotenuse of a unit-length right triangle? Maybe it is the secant of $45^{o}$? How you imagine $\sqrt{2}$ is dependent on the experiences you have had with it. The more limited our experiences with a mathematical object the more limited our understanding of it. The broader our experiences with the object the greater our understanding of it. $\sqrt{2}$ is an interesting object. What is it? What does it look like? How does it behave? What might a mathematics teacher do to provide opportunities for learner activity that broadens the learner's relationship with $\sqrt{2}$, making possible greater understanding of it and greater understanding in general of radicals?

Teaching mathematics for conceptual understanding has been characterized in a variety of ways. Whether it is called constructivist teaching (Gadanidis, 1994; Noddings, 1990; Wood & Sellers, 1997), teaching through problem solving (Lampert, 2001; Marrongelle, 2005), or teaching through inquiry (Borasi, 1992; Chissick, 2004; Goos, 2004), teaching for understanding is radically different from teaching by direct instruction (Simon, Tzur, Heinz & Kinzel, 2000). It is difficult for teachers who learned mathematics by direct instruction to grasp what is involved in teaching for understanding (Clarke, 1997; Ward, 2001). They may believe that students should be engaged in rich activity, including the use of manipulatives, using conversation, writing, and multiple representations to construct an understanding of the mathematics they encounter (Alberta Education, 2007). But what is involved in rich activity, and how might teachers identify, adapt, or even create such activity for their students? John Mason (2004) suggests:

> In order to provoke learners into taking initiative, into engaging fully with mathematical ideas and mathematical thinking, it is necessary to construct pedagogic tasks which call upon learners to make use of their undoubted powers of making sense. Those powers include imagining & expressing what is imagined; particularising, specialising, & generalising; conjecturing & convincing yourself and others; organising & characterising; focusing and

*Stephen P. Norris (Ed.), Reading for Evidence and Interpreting Visualizations in Mathematics and Science Education, 147–163.*

> de-focusing. These powers are involved in all of human sense making, but form the core of mathematical sense making. (p. 1)

We are particularly interested in pedagogic tasks that teachers create (Boston & Smith, 2009; Zazkis, Liljedahl & Sinclair, 2009) to provoke those powers, especially as they contribute to visualizing and reasoning (Chazan, 2000; Herbst, 2003; Sierpinska, 2004).

Theorists and researchers currently use 'visualization' as a label for strikingly different processes within the learning of mathematics (Emmer, 2005; Zimmerman & Cunningham, 1991). For example, Rodd (2010) uses visualization for a student's immediate and certain recognition of relationships among elements in two-dimensional geometric drawings. Yet within the van Hiele model for the growth of geometric understanding (Cirillo, 2009; van Hiele, 1999) visualization is the first stage of understanding, a recognition of common qualities among a set of geometric objects, a very different usage from Rodd's. Some mathematics educators distinguish among visualizing through graphing or sketching, creating a mathematical inscription on paper or a computer, and visualizing through forming mental imagery (Fisher & Hartmann, 2005; Whiteley, 2004).

In this chapter, we will describe the curriculum designed by one teacher who sought to provide rich and aesthetically rewarding experiences with square roots for her students. We will focus especially on what it meant for the teacher to design opportunities for students to develop a repertoire of images with which they could associate and construct related understanding for irrational numbers such as $\sqrt{2}$, that is, to understand the symbol as a referent for a particular amount, meaningful within its context and to be able to visualize various manifestations of the roots of non-perfect squares.[1]

In the teaching and learning described in this chapter, the students worked with paper cut-outs of squares and created inscriptions on paper both to think with and as final representations of their understanding. Whether or not the students were working with concrete materials, visible manipulatives, or inscriptions of their own making, we will use 'visualization' to refer to their visual images as mental constructs: "A *visual image* is taken to be a mental construct depicting visual or spatial information" (Presmeg, 2006, p. 207). Although our focus in this chapter is not primarily on inquiring into students' construction of understanding the idea of radicals, we have attempted to ensure that our use of 'visualization' is compatible with the notions of image-making and property-noticing in the Pirie-Kieren model of mathematical understanding (Martin, 2008; Pirie & Kieren, 1994).

## OBJECTIVE

It is one thing to visualize in geometry, where the mathematical objects are traditionally shown by sketches. Visualization of $\sqrt{2}$ is another matter. For numbers, such as whole numbers and fractions, our repertoire of images "began through compressing the process of counting to the concept of number and grew in sophistication through the development of successive concepts where processes were symbolised and used dually as concepts" (Tall, 2004, p. 29). We have found that most students have relatively few images of radical values as numbers (as quantities, measures, or positions), because their initial access to them was solely through computations and calculation processes (Suzuki, 2009). Yet there is a variety of geometric representations that can provide contexts in which square roots can have meaning as quantities and measures (Brown & Owens, 2009; Wagner, 2003).

For students to visualize numbers such as $\sqrt{2}$, it is necessary for teachers to provide opportunities for the students to encounter the numbers as meaningful within an accessible context. This brings us to the matter of curriculum design. In the manner of Christiansen and Walther (1986) and Sierpinska (2004) we will use 'task' to indicate the instructional process as designed, in this case by the teacher. The teacher, after selecting or designing the task for her students, led their engagement in that task. We use 'activity' to refer to the classroom processes through which the teacher's task is experienced by each student. We use the word 'experience' to point toward the embodied actions of each learner, as they engage with the task. We also recognize that mathematical activity, including visualization as a mathematical process (Alsina & Neilsen, 2006; Hanna, 2006), contributes to the learner's understanding of the discipline of mathematics. At the same time, as an embodied experience it contributes to the learner's identity as a mathematics doer. The goal of our chapter is to illustrate the development of a set of resources for occasioning student meaning making through visualization and reasoning.

## STUDY

In this project we worked with six teachers who designed curriculum resources for teaching specific high school mathematics content through inquiry. Those teachers planned for extensive use of visual imagery, concrete manipulative materials, visualization and reasoning in their inquiry. They also worked with the understanding that they were doing more than lesson planning and unit planning. Their work was curriculum development and intended for a broader audience than their own students. Hence, the teachers found themselves reflecting not only on the learning experiences they were trying to create but also on how these could be taken up by other teachers.

The teacher from whom the examples are drawn is a co-author on this chapter. This allowed us to discuss better the ways in which manipulative materials can be incorporated into lessons to engage the students' mathematical reasoning and visualization skills. The teacher's reflections and insights into creating curriculum for embodied learning are embedded throughout the chapter.

### *Curriculum for the Teaching of Radicals*

Radicals are an area of study in secondary school mathematics. In Alberta, students are to "explain and illustrate the structure and the interrelationship of the sets of numbers within the real number system;" "use basic arithmetic operations on real numbers to solve problems;" and "use exact values, arithmetic operations and algebraic operations on real numbers to solve problems" (Alberta Education, 2002, p.12). The specific outcomes (which the teacher interprets as open-ended) suggest that students classify numbers and use approximations and exact representations of irrational numbers in operations and problem solving. In addition to the Program of Studies that guides the teacher's instruction, there is also a provincially approved textbook series that schools provide students for use in their mathematics courses.

The textbook is a basic resource for the teacher as she plans for teaching and in the lessons she implements. An analysis of a commonly used textbook series Mathpower 9 (MP 9) (Knill et al., 1994) and Mathpower 10 (MP 10) (Knill et al., 1998) suggests that the outcomes are not as open-ended as the teacher understands them. In the textbook, radicals are introduced via their connection to measurement. However, this connection is briefly made and is rarely used as the concept itself becomes a mathematical object to work with. In the didactic elements of the grade nine textbook there are four geometric figures (four squares drawn on grid paper) in the lesson on square roots. In the grade ten textbook there are seven geometric images spread over two lessons (six images in one lesson and one in another). The first lesson refers back to triangles and the Pythagorean Theorem. In those examples values are used such that the length of the diagonal is an irrational number. The only other geometric image in the textbook lessons is used in the section in which students are learning to do operations with radicals (Figure 8.1). The task accompanying this figure is to find the lengths of the segments that make up the diagonal and to express the answers as a mixed radical. Given this task, we observe that the image is a means of posing an arithmetic exercise, not a means of understanding radical lengths.

An analysis of the textbooks used in grades 9 and 10 found that, of 304 questions posed in the exercise sets in the units on radicals, only 31 questions refer to a geometric figure / idea (Table 8.1).

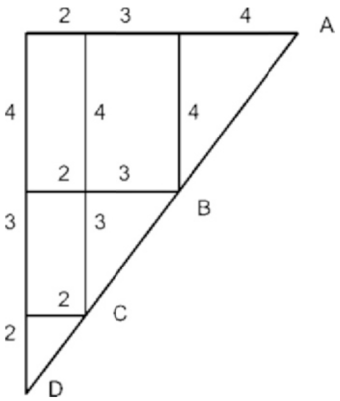


*Figure 8.1. Example from textbook that requires addition of radicals*[2].

*Table 8.1. Summary of Tasks in Textbook*

| *Text Year* | *Lesson* | *Exercises* |
|---|---|---|
| MP 9 | Introduce square roots via area and side length of squares; introduce notation (radical sign)<br>Estimating square roots and evaluating square roots with the aid of a calculator | 76 calculation questions; 24 calculation questions written as word problems; 7 problems that use square roots in their solution; 19 of 107 relate back to geometry (squares); 4 of 19 include a picture of a geometrical figure |
| MP 10 | Introduce irrational numbers as members of the Real Numbers Set: 3 exercises including diagrams of geometric figures are given that require the use of the Pythagorean Theorem to illustrate that irrational numbers can be constructed as line segments | 12 calculation questions; 19 classification questions |
| | Evaluating rational numbers<br>Cube roots are introduced as the inverse of cubing; evaluate with calculator<br>Definitions of radical, principle square root, index, radical sign and radicand<br>Operations with radicals (square and cube roots) done with calculator | 54 calculation questions;<br>10 application / word problems |
| | Simplification of radicals is introduced via equivalent expressions<br>$\sqrt{36} = \sqrt{4 \times 9} = \sqrt{4} \times \sqrt{9} = 2 \times 3 = 6$<br>showing their values are the same, all multiplying and dividing; properties are given for multiplication and division<br>$\sqrt{ab} = \sqrt{a} \times \sqrt{b}\ \ a \geq 0, b \geq 0$ | 71 simplifications; 4 application / word problems;<br>1 interpretation of property question (1 geometric figure) |
| | Operating with radicals and rationalizing the denominator a diagram is used to introduce $\sqrt{2}$ and students are asked to say why they are called like radicals; example offered for adding radicals (no explanation why you cannot add unlike radicals, the example simply does not do it) uses FOIL (mnemonic device) to multiply radical by a binomial<br>Definition and example of conjugate | 62 simplifications; 8 application / word problems<br>(8 geometric figures) |
| | Radicals in the context of the graphing<br>Exponents follow (laws taught in previous grade are revisited) | 22 calculations; 4 application / word problems. |

Contrast this summary of the unit from the textbooks used by the students with the teacher's overview for the unit (Table 8.2). In the overview we note her intention for the students to compare radicals with things they already know and be introduced to radicals as objects that have a geometric interpretation as well as an algebraic one. To do this the teacher introduces a "kit" which includes a variety of squares and right triangles whose dimensions include a radical measure. Based on the teacher's emphasis on building from what students know and heavy emphasis on concrete materials for exploring the concept of radical, and then operating with radicals using the concrete materials, it is clear the textbook does not provide adequate tasks and exercise sets for the learners to address either the ways of learning or the key elements she has articulated.

*Table 8.2. Teacher's Overview of Unit*[3]

| *Activities* | *Topics* |
|---|---|
| Comparing radicals to what we already know | Radical notation, fractional exponents as they sit in exponent laws, decimal equivalents |
| Meeting the radicals as objects to hold | Squares and right triangles<br>Equivalent radicals, mixed and entire radicals, adding and subtracting |
| Jumping into a more abstract space | Multiplying, dividing, rationalizing and problem solving |
| Using the kit | We use this kit to reinforce and generalize the learning about visualizing radicals:<br>Writing equivalent radicals<br>Adding and Subtracting radicals |
| Tool box | Exponent Laws<br>Equivalent Radicals<br>Multiplication as Area<br>Adding as Length<br>Decimal Approximation |

### *Teacher as Curriculum Designer*

From Table 8.2 we observe that the teacher outlines the unit from a student's perspective. That is, the teacher uses verbs and describes the actions that the students will take as they study the ideas. Further, she emphasizes a geometric perspective in contrast to a number perspective; that is, square roots as geometric objects (lengths of sides of squares—this is similar to introduction of perfect squares in the grade nine textbook). In the plan, she describes the general nature of the students' encounter with the content they are expected to learn in the unit of instruction. At the end of her notes there is a list of the students' toolkit, the mathematical objects, concepts and processes that the students have available to them via their previous experiences in mathematics classes. Because the teacher believed in the first instance that students should use concrete manipulatives to learn, that the tasks should make space for consolidating learning, and that the students need opportunities to demonstrate their understanding, she created a set of tasks that had the students work in a multifaceted environment. They would use what they knew and express that knowing through their inscriptions; they would work with concrete materials provided by the teacher to make deductions about measures and quantities; and they would keep records of their thinking in order to prompt pattern noticing. Finally, the teacher recognized that the concrete imagery the students were developing must work hand in hand with their analytical thinking (Presmeg, 1997). When creating the tasks for learners she asked herself: What does it mean to make mathematics approachable, friendly? Her answer was that it should be touchable—"I can hold in my hand." It should be familiar—"I've seen this before." It should be part of the student's mathematical history—"I've known this for a long time." And the student must believe she has influence in the situation—"I matter." Finally, unusual ideas are celebrated and less conventional thinking can guide class discussion (Sookochoff & Mercer, 2003).

Working from this heuristic and with these stated beliefs, the teacher developed and articulated the lessons through a series of tasks that structure the students' activity (Table 8.3). To begin this unit the students are invited to draw from their mathematical experiences very familiar squares (of area 1 and 4 or 9 and 16) and from that imagine or draw a square of area 2. Once students have been introduced to the square of area 2 they are offered the opportunity to work with concrete materials that will put $\sqrt{2}$ into their hands. It begins with a radical kit (Figure 8.2) and a series of tasks (Table 8.3). The kit (which the students cut out from paper) provides an opportunity to begin their exploration of radicals via embodied experiences working with squares of particular dimensions, specifically with an irrational side length beginning in the first task with $\sqrt{2}$. They then work with kits that have squares of side length $\sqrt{5}$, $\sqrt{10}$, and $\sqrt{13}$. The embodied experiences provide a space for working on visualizations of radicals. Seeing, holding and manipulating the cut-outs provide an experience for understanding square roots.

*Table 8.3. Teacher Developed Tasks*

| *Task Number* | *Description* |
|---|---|
| 1 | Think about perfect squares, [of area] 1 and 4. Draw them on graph paper. Now imagine or draw a square of area 2. |
| 2 | Determine the area of each square [Figure 8.2] with any method you wish. Record the area on each square. You know that a square of area 2 has a side length of ____. Label the side lengths of all the squares. |
| 3 | Cut out the squares from the handout. How many squares will stack to equal a square? Label this alternate way of expressing the side length. |
| 4 | Summarize your findings in a chart. |
| 5 | Using any pieces you like, find three different ways to stack squares to the same height as ____. [the blank is replaced by a number of different values] |

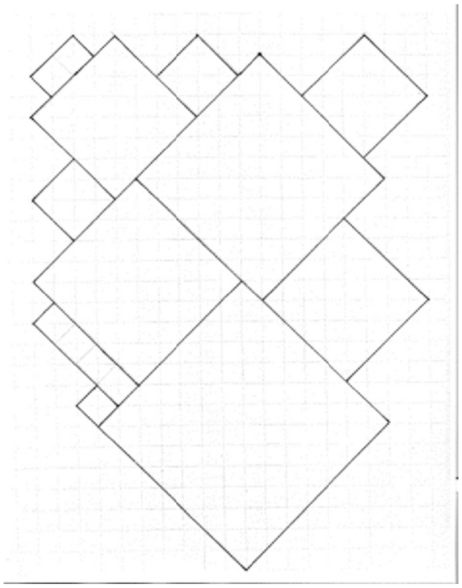


*Figure 8.2. Root Two Kit*

The first instructions given to the students are to find the areas of the squares and the length of the sides (for the squares in each kit). There is a number of ways students determined the areas of the squares as represented in the images reconstructed from student working papers and the teacher's board work: counted the unit squares (Figure 8.3);

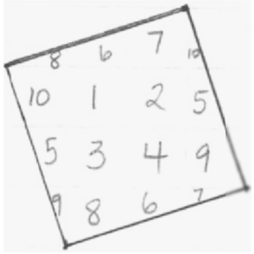


*Figure 8.3. Counting method.*

drew triangles to form a square of area that is easily determined and then subtracted from it the added triangles (Figure 8.4);

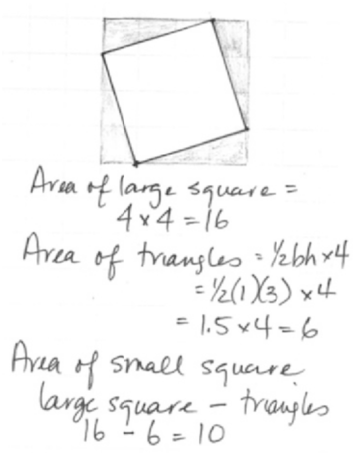


*Figure 8.4. Draw square of known area and side length.*

dissected the square into a central square with unit squares at right angles to the sides of the inner square and then calculated the area of the triangles on each of the four sides; added areas of triangles to area of inner square (Figure 8.5);

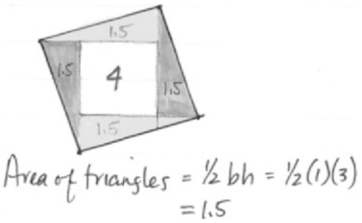


*Figure 8.5. Dissect into triangles and smaller square.*

or drew construction lines and used the Pythagorean Theorem to determine the length of the side (Figure 8.6).

Note in the student work the ways in which visualization and deductive reasoning contribute to the solution of the problem. In the first example (Figure 8.3), the student visualizes two partial pieces fitting together to create a unit square. The use of deductive reasoning is triggered when symmetry is invoked to determine that two specific pieces will fit together to form a unit. In the second and third examples (Figures 8.4 and 8.5) the student visualizes the right triangles that

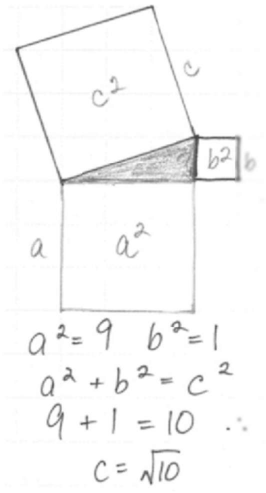


*Figure 8.6. Create right triangle on side of square.*

can be made on the sides of the square, then uses knowledge of the area of triangles to determine their area. A deduction leads to subtracting the area of the four constructed triangles from the area of the newly created large square. Again visualization is invoked when the student notes that a small square with sides at right angles to the unit squares can be dissected from the larger square leaving four right triangles. Knowing how to calculate the area of the right triangle allows the student to add the areas of the triangles to the area of the inner square. Finally, in our examples, we find the case of the learner who notes that right triangles can be constructed on each side of the square (Figure 8.6). From here a construction can be made that invokes the Pythagorean Theorem in which the large square is equal to the sum of the squares on the other two sides of the triangle.

It is important to note that the activity generated from these tasks is about more than $\sqrt{2}$. In this lesson students are encouraged to compare their strategies for finding the side lengths and to discuss how their methods are related. For example, students might note a relationship between the two examples where the area is constructed from a square plus four triangles or a square minus four triangles.

These four examples are used to demonstrate how this form of inquiry (as exemplified by Task 2, Table 8.3) occasions students' image-making as supported by their visualization and deductive reasoning to make meaning of the situation involving a radical (length of side). But the set of tasks calls for more than the deductive work of figuring out the length of the sides of a single square. In tasks 3 and 4 the teacher asks students to use their methods for finding the areas for a number of different squares (all multiples of root two). From here the students will construct a number of radical lengths to use as rulers and use those rulers to make sense of adding and subtracting with radicals (Figure 8.7 demonstrates using radical kits for measuring.). For example, three $\sqrt{2}$ sides are the same length as one $\sqrt{18}$ side. Students are instructed to keep a record of the lengths of the sides and to look for patterns and relationships between the entire radical and the mixed radical (Figure 8.8). This set of experiences with radicals provides the basis for the learner to understand the radical as a measure, the measure of the hypotenuse of right triangles, an exact number, the mixed form of radicals and entire radicals, a solution to an equation, and so on.

Finally, the teacher asks the students to consolidate and demonstrate their understanding of radicals through a summative activity "the radical picture". Through this activity the learner is able to demonstrate the knowledge she has of radicals. Figure 8.9 contains the instructions and an image the teacher offers the students as an example of the range of mathematical objects that they could demonstrate through the making of a "radical picture". Note the deliberate drawing of triangles and squares that include radical lengths. There are also multiple computations that involve radicals, as demonstrated in the calculations of area and perimeter. This summative activity provides the students an opportunity to demonstrate their attainment of all of the objectives of the radicals unit in grade 10 mathematics.

The set of tasks that the teacher designed for her students provides them with concrete opportunities to manipulate materials, images, and symbols from which they can build their understanding of (in this case) radicals. Those activities paid special attention to visualization in so far as students were working on developing new tools for their toolkit; that is, mental constructs that depicted visual images of radicals as measures, hypotenuses, and perimeters (Presmeg, 2006). Those mental constructs then supported student understanding of radicals, radical notation and operations on radicals, which were the major thrusts of this unit.

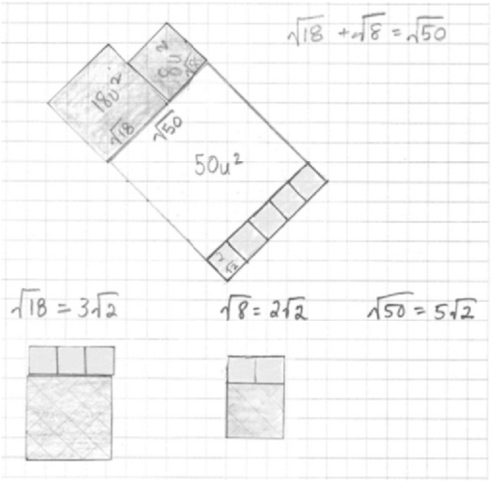
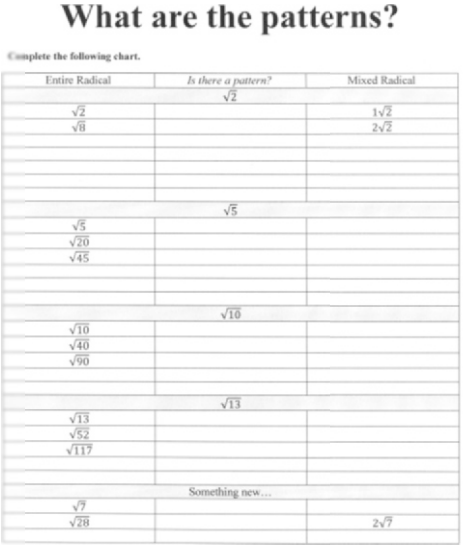


*Figure 8.7. Measuring with radical kits.*



**What are the patterns?**

Complete the following chart.

| Entire Radical | *Is there a pattern?* | Mixed Radical |
|---|---|---|
|  | $\sqrt{2}$ |  |
| $\sqrt{2}$ |  | $1\sqrt{2}$ |
| $\sqrt{8}$ |  | $2\sqrt{2}$ |
|  |  |  |
|  |  |  |
|  |  |  |
|  |  |  |
|  |  |  |
|  | $\sqrt{5}$ |  |
| $\sqrt{5}$ |  |  |
| $\sqrt{20}$ |  |  |
| $\sqrt{45}$ |  |  |
|  |  |  |
|  |  |  |
|  |  |  |
|  | $\sqrt{10}$ |  |
| $\sqrt{10}$ |  |  |
| $\sqrt{40}$ |  |  |
| $\sqrt{90}$ |  |  |
|  |  |  |
|  |  |  |
|  | $\sqrt{13}$ |  |
| $\sqrt{13}$ |  |  |
| $\sqrt{52}$ |  |  |
| $\sqrt{117}$ |  |  |
|  |  |  |
|  |  |  |
|  | Something new… |  |
| $\sqrt{7}$ |  |  |
| $\sqrt{28}$ |  | $2\sqrt{7}$ |
|  |  |  |

*Figure 8.8. Table for record keeping.*

## CONCLUSION

Curriculum policy makers are explicit about the nature of learning and the kinds of experiences students should encounter in the mathematics class:

> Students learn by attaching meaning to what they do, and they need to construct their own meaning of mathematics. This meaning is best developed when learners encounter mathematical experiences that proceed from the simple to the complex and from the concrete to the abstract. Through the use of manipulatives and a variety of pedagogical approaches, teachers can address the diverse learning styles, cultural backgrounds and developmental stages of students, and enhance within them the formation of sound, transferable mathematical understandings. At all levels, students benefit from working with a variety of materials, tools and contexts when constructing meaning about new mathematical ideas. Meaningful student discussions provide essential links among concrete, pictorial and symbolic representations of mathematical concepts. (Alberta Education, 2007, p. 1)

Comparing the textbook treatment of radicals and this teacher's treatment of it, we note stark differences between the two. Both are based on interpretations of the program of studies. Both use geometric images to introduce radicals as irrational numbers with which students can do computations. But they differ in profound ways. The textbook has extensive emphasis on calculating with radicals in the context of the symbolic realm. Very quickly, students are moved from geometrical interpretations and examples to computations over a large range of radical values. There is very little emphasis placed on visualization and on reasoning. In contrast, the teacher's lessons asked the students to work towards computational skills for radicals but did so through extensive work with root two and extending the knowledge developed working with root two to other radicals. In the teacher-designed curriculum, student activity was constrained, slow, deliberate, and repetitive. Although it involved computations, it emphasized deductive reasoning and visualization to come to understand how computations

| *Instructions* | *Marks* |
|---|---|
| Fifteen lines, each labeled with its length as an exact radical | 15 |
| Explain your calculations for 5 of the lines | 5 x 2 |
| Exact perimeter | 5 |
| Polish and presentation simplified radicals when possible variety of radicals used evidence that you have pushed yourself to learn all you can from the assignment | 15 |

*Figure 8.9. Summative activity: The Radical Picture.*

work in the context of radicals and the subtle differences in algorithms, form, and expression when operating on radicals compared with rational numbers, for instance.

A common error when students first find the sum of radicals is to add the coefficient and add the radical. Using a $\sqrt{2}$ ruler (described in Tasks 3 to 5 in Table 8.3), provides students with an opportunity to make sense of why only the coefficients are added and not the value under the radical sign. Contrast this approach with the textbook approach to teach addition of radicals. In the textbook a diagram of a right triangle made up of smaller right triangles is given to the students with measures noted and they are instructed to find the length of the hypotenuse (Figure 8.1). This example, is followed by a set of exercises in which the sums are expressed as equations to compute. The textbook approach involves practicing the computation skill prescribed in the lesson with a number of equations. In contrast the teacher's approach involved using the images and the students' visualization skills to create addition problems and demonstrate their solutions with multiple representations using the kits, diagrams, and equations.

About the lessons in this teacher's class, one student commented: "We drew a lot of things. We drew out the patterns to help us understand better." "I never really liked math. I am in it and getting better." Another student noted how the drawing stood out: "I thought that radicals was really fun. It helped me learn better. We had this project where we drew a picture and then [wrote] out the formulas." Yet another commented on how the hard work made a difference to her: "It helped me then I understood what she did on the test. My project related to it. You had to work hard at it so it stuck with you."

In the textbook there is a distinct lack of embodied experiences with radicals as quantities and as measures. Because of this teacher's orientation, the textbook resource was inadequate for teaching these lessons. When a teacher encounters such a gap in her primary curriculum resource she is left to either pull together alternative resources based on her pedagogical content knowledge that fit better with her pedagogical orientation and her understanding of the learner or to create new curriculum. In this case the teacher also had to deviate from her peers' interpretation of curriculum. She felt strongly that the embodied, creative, active, and deduction-rich approach was better for learners than proficiency and efficiency in radical arithmetic. The gaps in the textbook and her passion and intuition for deep conceptual understanding led the teacher to design and develop curricular resources specifically for her lessons.

This teacher took from her content knowledge, and her pedagogical content knowledge, and built curricular knowledge through her own constructive activity. She built a set of experiences that went well beyond the non-reflective paper-and-pencil exercises and unquestioned prescriptions for computational techniques promoted in the textbook resource. The learning theory literature tells us that these students will understand mathematics quite differently from those who reflect on repetitious exercises, or unpack techniques for computations, and those students will understand mathematics differently from those who build concepts and processes from kinesthetic experiences in space and time and with physical materials

(Roth & Thom, 2009). It is also significant to note that the teacher trusts that the students' meaning making through the explorations described in this chapter will pay off in their understanding of other content: slope and values of trigomometric functions are just two examples. The teacher is confident that in inquiry work such as described herein, multiple outcomes are addressed at once. She thinks of it as planting seeds.

In this chapter we offered an illustration of the curriculum and resources one teacher designed[4] to teach radicals to secondary school students. Lessons made use of embodied experiences with concrete materials to promote visualization, and reasoning—conceptual understanding of the content. We shared insights into her thinking about the didactiques and pedagogy[5] of her lessons to broaden our understanding of the kinds of tasks teachers might offer their students in inquiry-based lessons. In those lessons students developed tools for thinking mathematically. The radical kits, the experiences with root two that included cutting, measuring, counting, and expressing the enactive through iconic and symbolic representation of radicals all contributed to the learner's relationship with radicals. Because of the inquiry-orientated tasks in this teacher's lessons that invoked reasoning and visualization through concrete, pictorial, and symbolic activity, this teacher's students had opportunities to thoroughly experience $\sqrt{2}$. Imagine $\sqrt{2}$ for them.

## NOTES

[1] This work also leads the students into cubed roots but this will not be elaborated in this chapter.

[2] Adapted from Mathpower 10

[3] These notes were developed by the teacher in collaboration with a colleague and presented to other teachers at their annual convention (Sookochoff and Mercer, 2003).

[4] The teacher acknowledges that her thinking about radicals was influenced and supported by Tom Kieren and Ralph Mason.

[5] Our use of didactiques and pedagogy is based on our understanding of the French distinction where didactiques is the study of teaching and learning of a specific content area. This is in contrast to pedagogy which is much more general.

> The work of disciplinary didacticians is to take subject matter into account with its specificities and to study how a small piece of knowledge can be taught for better student learning. Pedagogy, as it is considered in France, is often related to educational theories developed by philosophers such as Montaigne, Rousseau, Dewey, or by practitioners who have written about their innovative practices in classrooms (Freinet, Montessori, etc.). Other issues developed in pedagogy are the students' personalities, teacher–student relationships, classroom atmosphere, learning styles and soon. (Caillot, 2007, p. 127).

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BRENDA J. GUSTAFSON AND PETER G. MAHAFFY

# 9. INTRODUCING GRADE FIVE STUDENTS TO THE NATURE OF MODELS

## INTRODUCTION

Creating models (understood as physical, visual, or mental representations of objects, phenomena, or processes) to represent scientific ideas has played a critical role in the development of scientific knowledge and continues to be part of the professional practice of science (Duit, 1991; Gobert & Buckley, 2000; Mathewson, 2005; May, Hammer, & Roy, 2006). Scientists generate, refine, and validate a wide variety of models to explain observations, communicate ideas, and make predictions about future events (Mathewson, 1999; May et al., 2006). With time, scientists may arrive at mutually agreed upon models that represent salient features of phenomena or processes. Often these models are featured in print and digital media resources used for communicating and teaching science.

In educational contexts, teachers use a variety of models (e.g., pictorial models, three-dimensional models, body movement models, computer animations) to help students understand scientific phenomena and processes that are complicated, unseen, happen over a long period of time, or are very large or very small (e.g., the water cycle, atoms and molecules, mountain building, and the solar system). Models are intended to support students to connect new ideas to what they already know, visualize abstract ideas, and construct a useful understanding of difficult concepts. But do students view these models in the ways teachers intend, and understand the strengths and limitations inherent to each model? Or do they sometimes believe models are literal representations of the real thing—a view that could result in misconceptions about science concepts? Elementary teachers readily acknowledge that their students can construct a variety of misconceptions about science concepts. However, teachers seldom identify and examine the role models play in the development of student conceptual understanding, including the development of misconceptions by learners.

Researchers caution that learning through models is not a straightforward business. Although models can be useful conceptual tools that provide another perceptual pathway to understanding (Mathewson, 1999), models are not foolproof (Harrison & Treagust, 2000a). Instead, a model can become a "handicap for students" (Holton, 1986, p. 240), and a potential "educational pitfall" (Mathewson, 1999, p. 47)—terms that should cause us to think carefully about model-based learning and teaching.

We speculate that one challenge to using models to teach science concepts lies with students being unfamiliar with the nature of models (Gustafson & Shanahan, 2008, 2010). Thinking about the nature of models (meta-modelling knowledge)

*Stephen P. Norris (Ed.), Reading for Evidence and Interpreting Visualizations in Mathematics and Science Education, 165–180.*

before and during science instruction appeared particularly critical in light of our focus—introducing Grade 5 (ages 10–11) students to the particle nature of matter. Teachers participating in our study would inevitably have to use an array of particle models in order to represent the unseen world. If students thought the models are literal representations of the real thing, did not understand that every model has strengths and limitations, or did not recognize the salient features of each model (all aspects of meta-modelling knowledge), then it was likely they would construct misconceptions about particles.

To help students develop an understanding of the nature of models (and particles) we created and piloted a variety of print teaching resources and digital learning objects (DLOs). Grade 5 teachers were asked to use their knowledge of models and particles to integrate these resources into their Classroom Chemistry unit (Alberta Education, 1996). Underpinning our work on the nature of models were at least two critical questions: What ideas about the nature of models would be useful within the context of learning about the particle nature of matter? Is there a relationship between students' views about the nature of models and their views of the nature of matter?

## RELEVANT LITERATURE

To inform the creation of the teaching resources, we drew from research in four areas: a) model-based teaching and learning in science, b) students' understanding of the particle nature of matter, c) designing digital learning objects, and d) using digital learning objects to teach chemistry. In this chapter we discuss the first of these four research areas leaving the remaining three areas to Chapter 10 in which we focus on the students' experiences of learning about the particle nature of matter.

### *Model-based Teaching and Learning*

As noted, models act as tools for thinking about phenomena and processes and are used for constructing explanations, making predictions, testing hypotheses, and communicating ideas (Erduran, 1999; Gilbert, Boulter, & Rutherford, 1998; Harrison & Treagust, 2000b). Teachers use these exploratory and explanatory functions to a) represent scientific concepts to students, b) help students create and evaluate personal mental models (understood as internal mental images or representations used to reason about phenomena), and c) encourage students to express those models in ways that provide insight into their developing understanding. Model-based teaching can help students create robust mental models by provoking thought about the target phenomena or process, representing the target in an understandable way, and supporting students to recognize salient features.

We caution, however, against an uncritical belief in the efficacy of models (Ainsworth & Loizou, 2003; Harrison & Treagust, 2000a). Studies of students using models to learn about scientific phenomena or processes show that outcomes may not match teachers' intentions and that, for some students, models present a barrier to understanding (Gobert, 2000; Harrison & Treagust, 2000b). One factor contributing to students' difficulties with models could be their naïve understanding of the nature of models. Students who have difficulty understanding that every model features strengths and limitations and that all models inevitably differ from the target phenomena, will likely have difficulty identifying the conceptual messages embedded in a model (Gobert & Discenna, 1997; Gustafson & Shanahan, 2010; Harrison & Treagust, 2000a, 2000b). Other factors identified in the literature as contributing to students' difficulties with models include existing misconceptions, having a naïve understanding of the phenomena, or possessing a low level of representational competence. This array of factors could lead to selective attention, dismissing key aspects of the model, a resistance to conceptual change, and a sense of frustration with simply being unable to see the real thing (Harrison & Treagust, 2000b; Yerrick, Doster, Nugent, Parke, & Crawley, 2003).

Challenges inherent to learning through models have led researchers to explore a variety of instructional strategies related to model-based learning and teaching. Attempts have been made to help students to overcome some of their perceptual and conceptual difficulties with models by: a) providing them with guided instruction about the nature of models prior to or during model-based learning (Gobert & Discenna, 1997; Gustafson, Mahaffy, & Martin, 2009; Gustafson & Shanahan, 2008; Gustafson, Shanahan, & Gentilini, 2009, 2010; Snir, Smith & Raz, 2003; Treagust, Chittleborough, & Mamiala, 2002); b) requiring them to work across multiple modeling contexts (Acher & Reiser, 2010; Buckingham & Reiser, 2010); or c) asking them to construct, analyze, and re-construct self-generated models (Baek, Schwarz, Chen, Hokayem, & Zhan, 2009; Schwarz et al., 2009).

Of particular interest to us was assessing how best to create print and digital teaching resources to provide students (and likely their teachers) with an introduction to the nature of models. Instruction about the nature of models should include practice in evaluating the strengths and limitations of multiple models (Boulter & Gilbert, 2000; Harrison & Treagust, 2000b; Snir et al., 2003); opportunities to create, evaluate, and revise self-generated models (Baek, et al., 2009; Justi & Gilbert, 2002; Schwarz et al, 2008; Windschitl, Thompson, & Braaten, 2008); analog-target mapping (Harrison & Treagust, 2000b); use of multiple models of the same phenomena to constrain the interpretation of each other and show there is no single correct model (Ainsworth & VanLabeke, 2004; Harrison & Treagust, 2000a, 2000b; Mathewson, 2005); and discussing the role of models in science (Acher, Arca, & Sanmarti, 2007; Grosslight, Unger, Jay, & Smith, 1991; Treagust et al., 2002). All these ideas have merit—the challenge is to identify ideas within reach of Grade 5 students and ways to present these ideas within the context of particle theory. Many questions remain about the extent to which meta-modelling knowledge might support conceptual understanding (Baek, et al., 2009; Fortus, Rosenfeld, & Schwartz, 2010).

## *Looking Ahead*

There are many challenges for teachers interested in supporting their students' understanding of the nature of models. Teachers likely need to develop their own understanding of the nature of models and consider what teaching strategies may help their students. Students need to be willing to take on the considerable work of critiquing multiple models and using this understanding of models to inform their developing understanding of science concepts. Many questions remained for our CRYSTAL—Alberta project. What should be the design of teaching resources that could help students understand the nature of models? Would students be able to understand the importance of using models to portray particles and be able to discern the strengths and limitations of these models? Would there be any link between the students' understanding of the nature of models and their ability to use ideas about particles to explain the observable properties of matter? We hoped this exploratory study would provide tentative answers to some of these questions and guide future studies.

## CRYSTAL—ALBERTA PROJECT

### *Creating the Teaching Resources*

In project Year 1, we began work on creating and piloting a print resource entitled Understanding Models in Science (Gustafson, Shanahan, Gentilini, Mahaffy, & Martin, 2007). This resource featured lessons in which students considered multiple models drawn from everyday life (e.g., globes, toy trucks), created their own pictorial models, and interacted with a variety of particle models (e.g., body movement models, 3D models). Concepts related to the nature of models included in this preliminary resource would in later project years be revised to become a core of 'big ideas' about models featured in revised print resources and digital learning objects: a) models are not exactly like the real thing, b) all models have strengths and limitations, c) models are 'good enough' (Millar, 2005) for representing some aspects of the real thing, d) a model is a representation of the real thing that can be used to help understand and share ideas about the real thing, e) there are many different kinds of models (e.g., body movement models, pictorial models, 3D models), and f) people can generate their own models of the real thing. In the following sections, we present a selection of study data intended to show students' thinking about the nature of models.

### *Existing Ideas About Models*

We explored students' existing ideas about models using worksheets and pre-study surveys that required them to respond to generic questions, such as: What is a model? What are models used for? and Are models ever exactly like the real thing? For most students, models were fashion models, role models one looked up to, toys, figures or statues, smaller versions of the real thing, or something that looks like the real thing—answers similar to those given in other research studies that have explored students' existing ideas of models (Grosslight et al., 1991). For many students, models were used to show or display something else; and to show how to be, entertain, and explain something else. Students were divided about whether or not models were exactly like the real thing and this variability tended to hinge on how they defined 'model'. For example, a student who wrote that a model is a role model then wrote, "No, [a model is not exactly like the real thing] because you can look different from your role model". Another who thought a model was something like a model airplane then wrote, "Yes, models [are exactly like the real thing because they] are for seeing things little instead of the actual thing". What we hoped to see, however, were at least some students who thought models represented a real thing but were not exactly like the real thing, could explain differences between the two, and wrote that models helped to understand or explain the real thing. In general, over the years of the project, about one quarter of the students responded in this way.

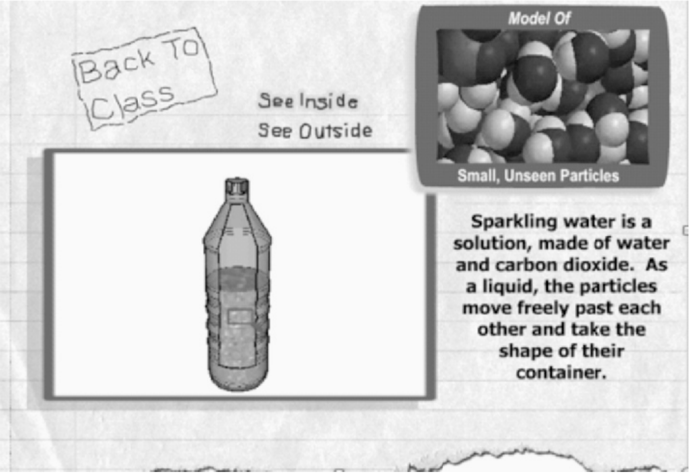
We were particularly interested in students' responses to questions about how models might be similar to or different from the real thing. We speculated that as we presented particle models, students' perceptions of model-target correspondence would likely play a role in their conceptual understanding of particles. Therefore, we explored the students' existing ideas of a common classroom model—a globe (Gustafson & Shanahan, 2010). Almost every student agreed that a globe was a model of the Earth. Their familiarity with the model and the real thing helped many to write about the strengths (e.g., it spins like the Earth, it shows locations of land and water, it is spherical) and limitations of the globe (e.g., it is a different size, it is plastic, it is made by people, it does not show everything, some colours are incorrect). Many students added that the globe was useful for "providing a visual," "showing what the Earth looks like," and "showing destinations." Despite most students' understanding that the globe was a model of the Earth and that there were differences between the two, some ideas would not be helpful for understanding particle models. For example, some students wrote the globe was "a replica", "a smaller version," and that it "shows the real things"—ideas in need of much refinement in order to be useful within the context of particle models.

### *Shifting Views of Models*

In our Understanding Models in Science print resource, we used four anchoring questions designed to encourage students to develop an understanding of the nature of models: a) How is the model like the real thing? b) In what ways is the model not like the real thing? c) In what ways does the model help you understand the real thing? and d) What incorrect ideas could people have if they believed that this model was the real thing and not the model? Students revisited these questions as they considered familiar exemplars (e.g., a globe as a model for the Earth) and models used to introduce the particle nature of matter (e.g., seeds shaken in a jar to model solids, liquids, and gases; body movement modeling particle movement in solids, liquids, and gases). In addition, students were encouraged to develop their own models for some phenomena (e.g., creating a pictorial model of air in a balloon) as a way of helping them grow in their understanding of the nature of models (e.g., people create models, models help to understand some aspects of the real thing, a variety of models can be used to depict the same idea). We viewed opportunities for students to talk with each other and the teacher as key to developing an understanding of the nature of models and we wondered if the students' views of the nature of models would develop consistently throughout instructional sequences.

As students worked through the aforementioned models, there was an overall growth towards understanding that the particle models were analogical tools featuring a variety of strengths and limitations (Gustafson et al., 2010). Despite this overall growth, a closer look at the students' responses to worksheet questions showed that students' ideas about the strengths and limitations of a model could vary with the model under consideration. For example, a student able to identify strengths and limitations of a self-generated model of air in a balloon could struggle to critique the seeds-in-a-jar model but then write about helpful and unhelpful ideas portrayed in the body movement model. In the end, there was some evidence that students who were able to move beyond a naïve realist perspective of models (seeing either an exact correspondence between the model and the real thing or only seeing the model as a miniature or magnified version of the real thing) to exhibit what we termed an evolving view of models (ability to recognize that models are analogical tools with complex strengths and limitations) were more likely to express a particle view of matter. However, variations among students and between contexts remained. Overall, the data suggested that students' ideas about models and particles were unstable, transient, and context-dependent. In these first stages of understanding, students' ideas about models could vacillate between naïve realist and evolving views. Ideas about particles appeared similarly unstable.

The most convincing evidence of students' unstable views of the nature of models was seen when the students wrote about viewing the Virtual Classroom digital learning object at the local science centre. The chemistry program at the centre encouraged students to participate in a variety of hands-on activities and revisit some ideas about the nature of models (e.g., 'good enough' models help to understand the real thing). As the students viewed the Virtual Classroom DLO, the program facilitator clicked on objects featured in a classroom scene (e.g., a basketball, a bottle of water) to portray dynamic representations of the particles making up the object (see Figure 9.1). Later, students' worksheet responses revealed that they all viewed these representations as copies rather than models of reality. In discussing these results, we speculated that several factors likely played a role in students' reverting to a naïve realist perspective of models: a) the scientific context of the chemistry program could have lent a sense of authority to the DLO models—a 'finally we're seeing those small, unseen particles at the science centre' reaction; b) the cognitive load of viewing colourful, dynamic models might have overwhelmed the students; and c) students had no time to discuss or manipulate the DLO (Gustafson et al., 2010). Despite this naïve realist view, the majority of students (7/10) whose responses could be categorized wrote about how the DLO showed that particles constitute matter and behave differently in solids, liquids, and gases. This was unsurprising considering how they agreed that the DLO enabled them to watch the real particles.



**Sparkling water is a solution, made of water and carbon dioxide. As a liquid, the particles move freely past each other and take the shape of their container.**

*Figure 9.1. Screen capture from the project Year 2 version of the Virtual Classroom digital learning object.*

Although data showed students were developing the ability to write about the particle nature of matter, data also raised important questions about the stability of their ideas and the role of instruction about the nature of models (Gustafson et al., 2010). First, we wondered if the students' transient, unstable views about particles were an inevitable precursor to a deeper understanding of particles. If so, then what supports would be needed in order for students to negotiate multiple models of particles, notice salient features, and understand relationships among models presented in DLOs? Second, if students could construct helpful ideas about particles by believing that DLO models were exactly like the real thing, then why even address the nature of models in future DLOs? Conversely, if we did think it was important for students to understand that DLO models were not exactly like the real thing (primarily because a naïve realist belief could lead to misconceptions about particles, a resistance to conceptual change, and a retention of models beyond their 'use-by date' [Harrison & Treagust, 2000b]), then how could we embed a more explicit critical stance towards models in future DLOs?

### *Sorting through Models*

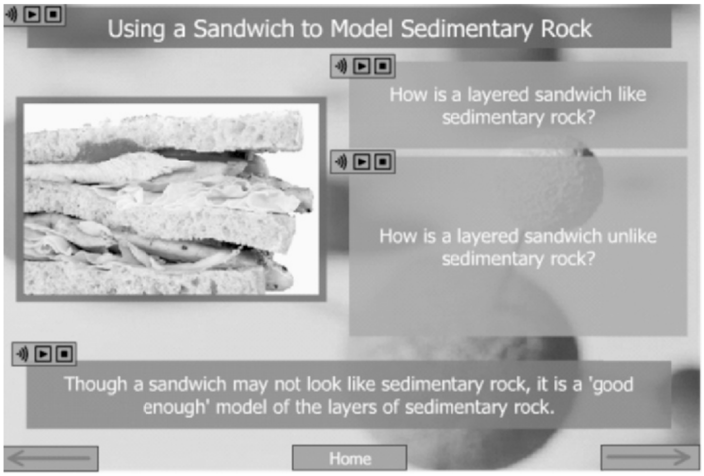
The sequence and design of ideas about the nature of models used in our DLOs was informed by data from students. In year 4, teachers were asked to teach their Classroom Chemistry unit as planned and at their discretion to integrate the six DLOs into their classroom activities. Although all six DLOS contained text that reminded students they were viewing models, Module 1 (Models in Science) and Module 2 (Models of Matter) provided explicit information about the nature of models. The following paragraphs focus on one of the Grade 5 classes that piloted these DLOs.

Module 1 began with screens where students were guided through analog-target mapping (mapping between the model and the real thing) using familiar exemplars (e.g., a globe and the Earth, a photograph of a girl and the real girl, a building block model of the CN tower in Toronto and the real tower). Using these familiar contexts, students were introduced to the ideas that a) a model is a representation, b) a model helps to understand and share ideas about the real thing, c) models are not exactly like the real thing, d) models are 'good enough' to understand some aspects of the real thing, and e) there are many kinds of models. Module 1 then asked students to generate their own models for sedimentary rock (topic selected because Rocks and Minerals were taught in an earlier grade) and provided a sample model on a subsequent screen (see Figure 9.2). Throughout these experiences, students were asked to think about the strengths and limitations of each model, and screen rollover questions lent support to students' thinking by providing sample answers.

At the end of Module 1, all students agreed that a model was not exactly like the real thing. More open to question were their reasons for distinguishing between the two. Out of the 22 students, 17 wrote that "models are only *like* the real thing" (emphasis added), "they are smaller versions," "they are replicas," and "they look different." This was unsurprising as most of the module's exemplars did portray models that resembled the real thing (e.g., the girl in the photograph looked like the real girl, the globe looked like the Earth, the models of the CN tower in Toronto looked like the real tower). Even the sandwich could be interpreted as looking like sedimentary rock due to the appearance of layers. Interestingly, students struggled to generate their own models for sedimentary rock. Instead of drawing sandwiches, lasagne, or any variety of layered objects, the students tended to draw pictorial models featuring layers of sand, rock, and soil—pictures that attempted to depict real sedimentary rock. We speculated that, although students understood that a model is not exactly like the real thing, criteria used to distinguish between the two had yet to develop to any depth in their thoughts.

The classroom teacher followed up on Module 1 with a discussion about what a model is (a model is a representation of a object, event, or idea) and why models are useful (help to understand and explain the real idea or thing). She guided the students to discuss the three states of matter (solid, liquid, and gas) and had them draw examples of solids, liquids, and gases.

We were aware that students' ideas that models were simply smaller versions of the real thing could lead to misconceptions about particle models. We were, however, mindful of students who previously had viewed the Virtual Classroom DLO. Those students, appeared to believe that particle models showed the real thing and this belief had likely helped them record helpful particle ideas. Still open to question was whether students would be able to distinguish between particle models and the real thing and whether they would see a payoff to doing so.



Using a Sandwich to Model Sedimentary Rock

How is a layered sandwich like sedimentary rock?

How is a layered sandwich unlike sedimentary rock?

Though a sandwich may not look like sedimentary rock, it is a 'good enough' model of the layers of sedimentary rock.

*Figure 9.2. Screen capture from Module 1 showing rollover questions that supported students' understanding of the model's strengths and limitations.*

Module 2 began with asking students to recall the observable properties of solids, liquids, and gases they had discussed with their teacher. After viewing a screen in which they watched a video clip of a pop can being opened (an example of a solid can, liquid pop, and gas bubbles) and were reminded of the observable properties of pop, the following text appeared: "Scientists believe we can explain these properties by thinking about the arrangement and movement of the small, unseen particles that make up matter". To set the stage for introducing ideas about unseen particles, the module used familiar entry points (e.g., washing our hands to kill unseen germs) to remind students that they likely already believed in an unseen world (see Figure 9.3). Further, students were reminded that believing in the unseen held a payoff—their understanding of germs was likely to lead to better overall health and fewer visits to the dentist. Underpinning this approach was research that viewed the transition to a particle world view as involving an ontological transition (Nakhleh & Samarapungavan, 1999)—abandoning the belief that matter was made of hard or soft continuous stuff and moving to the belief that matter was composed of small, unseen, moving particles. We wanted students to understand that making what might be a leap of faith to believing in small, unseen particles would have a payoff—small, unseen particles would help explain the observable properties of matter.

Introducing ideas about small, unseen particles in the remaining modules meant relying on text and visuals. Therefore, the Module 2 screen in Figure 9.4 prompted students to recall what they knew about models with most students recalling that models are never exactly like the real thing. Subsequent screens used familiar models (e.g., pictures of static building blocks, a dynamic model of dancing leprechauns, dynamic spherical models) to portray some first ideas about particles—particles are too small to see, particles can join together, particles move, particles have spaces between them, we do not really know what particles look like but they do not look like the DLO models, and particles are not coloured.

Believing in Something We Cannot See

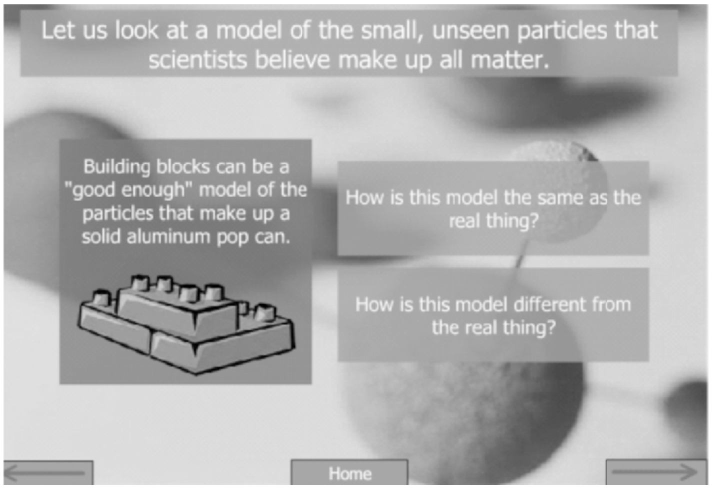
We cannot see lots of things but we still know they exist. Believing in something we cannot see influences our thinking and our actions.

We cannot see germs with our eyes, but we believe that germs exist. This belief keeps us healthy. If we wash our hands after using the bathroom then we are less likely to get sick.

We cannot see sugar in pop, but we believe the sugar exists. This belief keeps us healthy. If we drink less pop then we are less likely to gain weight and get cavities.

Believing in something we cannot see helps us understand something we can see.

*Figure 9.3. Screen capture from Module 2 showing familiar entry points to the unseen world.*



Let us look at a model of the small, unseen particles that scientists believe make up all matter.

Building blocks can be a "good enough" model of the particles that make up a solid aluminum pop can.

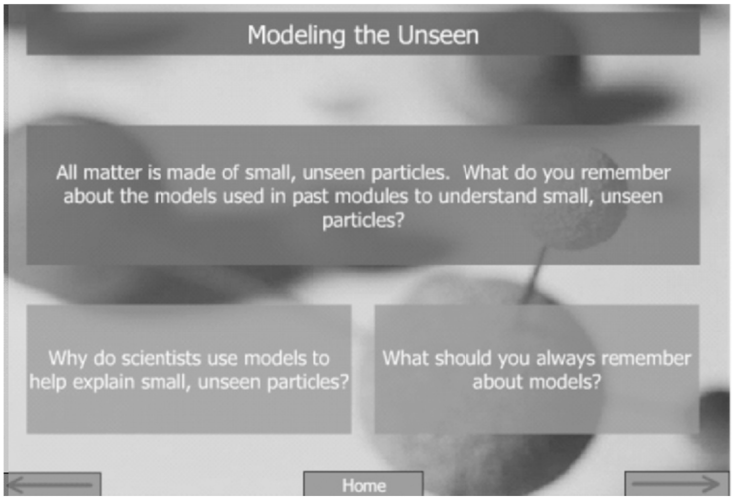
How is this model the same as the real thing?

How is this model different from the real thing?

*Figure 9.4. Screen capture from Module 2 showing static model of building blocks and two rollover questions.*

The building block particle model (in addition to other particle models featured in Module 2) repeated two rollover questions and provided accompanying answers that encouraged students to understand that every model had strengths (small things can join together to make bigger things) and limitations (particles are too small to see, particles do not fit together like building blocks). Rollover questions that included answers were a necessary design support for these screens of information. We could not expect students to interrogate the strengths and limitations of these models when for many this was their first formal encounter with ideas about particles. Excluding this information would have left the students wondering about how to analyze the strengths and limitations of the models and how to determine which features of these models could potentially help to understand about particles—an ‘open discovery’ approach that might constitute intellectual abandonment. Conversely, the information might have led to some students’ wondering, ‘If particles do not join together like building blocks, then how do they join together?’ and ‘Just how small are these particles?’ Throughout the final four modules, images of particles were consistently referred to as models and, periodically, students were reminded that models do not resemble the real thing (see Figure 9.5).

At the end of the study we asked students questions about the nature of models that paralleled those in the pre-study survey. Most students thought that a model was a representation or approximate copy of something else (e.g., “A model is something similar to the real thing”) and that a model is used to see or show something (e.g., “Models show what it might look like”, “Models are used to see up close”). All students agreed that a model was not exactly like the real thing (e.g., a model could differ in modality, size, or colour). Using the example of a globe, students once again agreed that the globe was a model of the Earth and based this response on their understanding of the strengths and limitations of the model. In retrospect, we should have provided them with a screen shot of a spherical model of particles and asked them the same question (e.g., Could these spheres be called a model? Explain.). Be that as it may, the students’ responses showed growth away from their initial ideas that models were fashion and role models towards a much wider definition. They were also now definite in their view



Modeling the Unseen

All matter is made of small, unseen particles. What do you remember about the models used in past modules to understand small, unseen particles?

Why do scientists use models to help explain small, unseen particles?

What should you always remember about models?

*Figure 9.5. Screen capture from Module 4 showing rollover questions reminding students of the nature of models.*

that models were not exactly like the real thing, and, if familiar with the model and the real thing (e.g., globe and the Earth), were able to identify distinguishing characteristics that went beyond writing that they were "somewhat different" or "not exactly alike."

Understanding the nature of particle models remained challenging. Despite including support in the DLOs for understanding the strengths and limitations of some of the particle models, in the post-study survey only a few students included this terminology in their answers. For example, when asked to explain a screen capture of a pop can juxtaposed with an image of spherical particles in the solid state, only three students wrote that this showed a "model of particles holding tight together." Remaining students wrote about how this showed the arrangement and movement of particles constituting the can and made no mention of viewing a model. Again, inserting a specific survey question asking about the strengths and limitations of the spherical particle model, or interviewing the students about their answers might have revealed greater insight into how the students were conceptualizing the nature of particle models.

We also acknowledge that although we used a variety of particle models in Module 2 (spheres, building blocks, and dancing leprechauns), in remaining modules we exclusively used spherical models to illustrate particle behaviour. This dependence on spherical models was adopted in order to reduce the cognitive challenges and visual complexity of moving between multiple models that featured what could be distracting differences (e.g., using spherical models of solids, liquids, and gases interspersed with building block models of solids, liquids, and gases). Although including a variety of depictions may have helped students understand that all visuals were models and alerted students to the need for thinking critically about each model's strengths and limitations, we were concerned that a variety of DLO models could also represent a barrier to learning at this early stage. Future research into the trade-offs between relying upon spherical models and continuing with a variety of particle depictions would provide some insight into whether this is a critical factor influencing students' thinking about the nature of models.

## SUMMARY AND CONCLUSIONS

Students expanded their definition for models each year. Initial ideas that models were fashion models, role models, and toys were quickly changed to the idea that models included a variety of objects that were not exactly like the real thing. Students were able to identify the strengths and limitations of familiar models based on real things (e.g., globe and the Earth) but varied in their ability to write extensively about these similarities and differences. For example, some students could critique familiar models at an impressive level while others simply identified a difference in size.

Students encountered more difficulty creating models even if they were familiar with the real thing (e.g., sedimentary rock). Drawings showed that students needed support to identify salient features of the real thing, take a step away from the real thing, and think creatively about a model that could be used to capture and represent these salient features. This cognitive exercise would likely need to be informed by the role of models in science and how, for elementary students, models could primarily be a useful tool for a) showing how they were making sense of a phenomena, and b) communicating important ideas to others.

As the students encountered a variety of particle models in their classroom and in the DLOs, they could easily critique aspects of some models (e.g., particles do not look like people, seeds, building blocks, or leprechauns), but at other times they appeared to believe all aspects of the models (e.g., the spherical models show the particles). Several factors likely contributed to these observations. In these beginning stages of constructing an understanding of models and particles, it could be easy or challenging for students to link new ideas to their existing knowledge. For example, the ideas that models have a broader definition than they already thought, that a model was not exactly like the real thing, and that unseen particles do not look like people were easy to accommodate with existing ideas. Much more difficult was the idea that DLO particle models do not look like particles. We could almost hear the students thinking, "Okay, the particles do not look like people, seeds, building blocks, dancing leprechauns, or spheres—so what do they look like?". At a time when students were trying to understand particles, and create mental models of those particles, they were being told that there was no definitive pictorial model for particles. This 'it does not look like this but can be explained by this' approach presented great cognitive demands making it difficult to integrate with existing ideas. Facing this challenge, students' final survey responses showed they were willing to repeat that particle models were not exactly like the real thing (but were not particularly sure how they varied), and that most were using the idea that particles were spherical to understand the observable properties of matter.

We return to the question of whether it was worthwhile to include ideas about the nature of models when many students wrote helpful ideas about the particle nature of matter without any consistent written acknowledgement that they were working with models (see more in Chapter 10). As described in our data from Year 2 (Gustafson et al., 2010), an examination of students' thinking showed that those who exhibited an evolving view of models were more likely to express a particle view of matter. Year 4 project students who were at least able to write that what they had seen in the DLOs was not exactly like the real thing (whether or not they could take this idea any further) might be more willing in the future to consider alternative complementary models that do not feature spheres.

We identify the need for interviews and direct survey questions (e.g., Is this what particles really look like?) to shed more light on whether or not the students thought the static and dynamic coloured, spherical models portrayed in the DLOs and surveys were indeed models and how they thought these models differed from the real thing. Future studies incorporating these data collection methods would certainly add to our understanding of students' ideas about the nature of models. In the end, omitting ideas about the nature of models while emphasizing spherical particle models in much of the DLOs might have led to students' constructing an unassailable, difficult to change mental image of spherical particles—an image useful only in some contexts.

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# 10. USING COMPUTER VISUALIZATIONS TO INTRODUCE GRADE FIVE STUDENTS TO THE PARTICLE NATURE OF MATTER

## INTRODUCTION

Secondary school science programs have long included instruction to help students understand the physical world at three interconnected levels—the observable, the particle, and the symbolic (Johnstone, 1993). Elementary school (ages 5–12) science programs, however, emphasize understanding at the observable level only beginning with early childhood explorations of sand and water and progressing to common definitions for the observable properties of solids, liquids, and gases (e.g., liquid flows and takes the shape of the container). Lending support for a focus on the observable is the Common Framework of Science Learning Outcomes K-12 (Council of Ministers of Education, 1997) which expects students ages 10–11 to classify solids, liquids, and gases and identify physical and chemical change all without reference to particles. The National Science Education Standards (National Research Council, 1996) go further by cautioning that for students ages 10–14 it is premature to introduce the particle level as doing so can "distract from the understanding that can be gained from focusing on the observation and description of macroscopic features of substances…at this level…few students can comprehend the idea of atomic and molecular particles" (NRC, 1996, p. 149). These Canadian and American documents reflect a perspective on learning about the physical world that maintains that students must reach a certain developmental level before they have sufficient cognitive capabilities to understand matter at the particle level.

Perhaps we should reconsider the status quo and think about what might be gained by introducing elementary school students to some beginning ideas about the particle nature of matter. Informal conversations with elementary teachers in both Canadian and International contexts reveal two threads: a) some already refer to ideas about particles in response to student questions that demand particle answers (e.g., Why are liquids able to flow?), and b) students who have already heard terms such as 'molecules' and 'atoms' attempt to use these terms—sometimes incorrectly—to explain the observable properties of matter. Including ideas about particles in elementary school programs would provide teachers with guidance about concepts and explanations that could be used with students and provide another way to connect topics such as chemistry and weather. Furthermore, we speculate that exclusive emphasis on the observable properties of matter in elementary school might well contribute to misconceptions observed in secondary

*Stephen P. Norris (Ed.), Reading for Evidence and Interpreting Visualizations in Mathematics and Science Education, 181–202.*

and post-secondary students (e.g., solids are made of hard matter, liquids are softer matter that can flow, gas is made of invisible matter) (see, e.g., Boz, 2006; Sanger, 2000). If this is the case, then reconsidering the place of particle explanations within elementary school programs may be worthwhile.

Introducing elementary school students to the particle nature of matter poses challenges for both students and teachers. It is difficult for students (and likely adults) to believe that matter is made of small, unseen particles and to understand that the behaviour of these particles can account for what they observe. Teachers are faced with using models (understood as the physical, visual, or mental representation of objects, processes, or phenomena) of particles such as pictorial models and body movement models that are never exactly like the real thing—a situation that can lead to even more misconceptions. Furthermore, elementary teachers may be uncertain about their science subject matter knowledge (Appleton, 2002; Gustafson, Guilbert, & MacDonald, 2002) and require guidance to understand the subtleties of particle behaviour.

We started with the approach that learning science *through* models might helpfully be informed by knowledge *about* 'good enough' (Millar, 2005) models (for a discussion of meta-modelling knowledge, see Chapter 9) We then created print resources and digital learning objects (DLOs) that teachers could use to help introduce Grade 5 students (ages 10–11) to the nature of models and the particle nature of matter. Grade 5 was selected due to a) the province of Alberta's elementary science program Classroom Chemistry unit that included emphasis on the observable properties of matter (Alberta Education, 1996), and b) plans to include the particle nature of matter in a future revised Alberta program. We did not view the DLOs as panaceas for the challenges of introducing particles to students. Rather, the DLOs were intended to be integrated with teachers' existing strategies (e.g., having students participate in body movement models, building 3D models, generating their own models, and discussing multiple representations) that we believed would be critical to constructing a beginning understanding of particles. We did, however, think DLOs had some design features that could provide students with another useful pathway to understanding particle concepts. These affordances (understood as the perceived and actual physical properties of the DLOs) (Gibson, 1977; Pea, 1993) included design features that allowed students to view and manipulate particle representations, view observable properties juxtaposed with particle representations, view a variety of dynamic representations, and learn at their own pace.

## RELEVANT LITERATURE

To inform the creation of print resources and digital learning objects, we drew from research in four areas: a) model-based teaching and learning in science (see Chapter 9), b) students' understanding of the particle nature of matter, c) designing digital learning objects, and d) using digital learning objects to teach chemistry. In this chapter we will discuss the last of these three research areas.

### *Understanding the Particle Nature of Matter*

Early work by Novick and Nussbaum (1981) showed that students attempting to accommodate the observable properties of matter with the particle nature of matter idea must overcome “basic cognitive difficulties of both conceptual and perceptual nature” (p. 187). Since this work, other researchers have confirmed that difficulties with understanding the particle nature of matter abound across all ages and identified a variety of ideas that appear particularly challenging (Bunce & Gabel, 2002; Litchtfeldt, 1996; Nakhleh & Samarapungavan, 1999; Sanger, 2000). These ideas include particle scale and appearance (Ferk, Vrtacnik, Blejec, & Gril, 2003), the movement and arrangement of particles in different physical states (Boz, 2006; Eilam, 2004; Johnson & Papageorgiou, 2009; Tsaparlis & Ntalaouti, 2010), the discontinuity of matter (Snir, Smith, & Raz, 2003), how particles join (Ozmen, Demircioglu, & Demircioglu, 2009; Smithenry, 2009), and using particles to explain the observable properties of matter (Cook, Wiebe, & Carter, 2008; Kenyon, Schwarz, Hug, & Baek, 2008). Researchers working mostly with secondary and post-secondary students reason that a variety of factors likely contribute to students’ difficulties: a) students experience conflict between their existing ideas about matter and ideas about particles and they are reluctant to abandon existing ideas that have proved useful for understanding the observable properties of matter (Albanese & Vincentini, 1997; Eilam, 2004); b) shifting to a particle world view might involve an ontological transition (Nakhleh & Samarapungavan, 1999); and c) students may not have the representational competence or visual skills needed to view different representations, understand how they connect, and explain how each representation suits a particular purpose (Ferk et al., 2003; Kozma & Russell, 1997; Schwarz et al., 2008; Snir et al., 2003).

With these challenges in mind, some researchers have introduced aspects of the particle nature of matter to elementary students on the grounds that early work with students may help them construct preliminary ideas and develop appropriate skills that will ease the transition to a particle world view. Strategies that appear to hold some promise include asking students to construct and critique series of self-generated particle models (Baek, Schwarz, Chen, Hokayem, & Zhan, 2009; Schwarz et al., 2009), introducing the particle model within the concept of substance (Johnson & Papageorgiou, 2009), and using contexts linked to everyday life (Tsaparlis & Ntalaouti, 2010). Other researchers concerned with identifying appropriate particle concepts for students have developed learning progressions describing an approximate sequence that could be used in elementary and secondary schools to teach and assess concepts about matter and particles (Smith, Wiser, Anderson, & Krajcik, 2006; Smith, Wiser, & Carraher, 2010). Underpinning all of this work are at least two critical questions: 1) What concepts are helpful for constructing a beginning understanding of the particle nature of matter? and 2) How can these concepts be taught to elementary students while acknowledging that teaching must inevitably rely on using an array of ‘good enough’ models (Millar, 2005) that feature a variety of strengths and limitations? Of particular interest to our work was whether or not digital learning objects could play a role in supporting students' conceptual understanding of models and particles.

### *Designing Digital Learning Objects*

Researchers interested in designing digital learning objects have drawn from a variety of theories that help explain how viewers process information appearing in DLOs. Specifically, researchers have used dual coding theory (Paivio, 1990), cognitive load theory (Sweller & Chandler, 1991, 1994), multimedia learning theory (Mayer, 2001; Mayer & Moreno, 2002), and more recently social constructivist theory (Kozma, 2000; Roth, 2009) to explain interactions between viewers and DLOs.

Dual coding theory (Paivio, 1990) explains how information is stored and retrieved from memory using two processing systems—visual and verbal—that can interact to represent and connect incoming information. In this theory, text is processed, stored, and retrieved using the verbal system while pictures and graphics are processed using verbal and visual systems (dually coded). Information encoded in both systems can be easier to understand and recall, suggesting a role for images to complement or be used in lieu of text (Donovan & Nakhleh, 2007; Rieber, Tzeng, & Tribble, 2004).

Dual-coding theory, cognitive load theory, and multimedia learning theory share the view that students primarily draw upon working memory (and to an extent, long-term memory) to make sense of information presented in DLOs. All these theories acknowledge, however, that working memory is limited. Therefore, when DLO designers select various design elements they must remain aware of the cognitive load imposed on working memory. Complex displays and seductive details (e.g., imposing colour when this feature may not be critical to understanding screen content) (Mayer, Heiser, & Lonn, 2001) can mislead, overload, and overwhelm viewers, which highlights the need to reduce demands on working memory in order to facilitate learning (Chandler, 2004; Lowe, 2004).

Social constructivist theory emphasizes the social rather than the individual nature of learning (Gustafson & MacDonald, 2005). Instead of viewing students as taking in and processing information presented in DLOs, more emphasis is placed on the social and cultural context in which learning occurs. Digital learning objects are viewed as another tool students and teachers can use to talk and listen to each other. Through conversation students can learn how to see in a scientific way, tune into salient features of the DLOs, and construct an understanding of embedded concepts (Roth, 2009, 2010).

There are mixed results on how various DLO design features affect learning (Ainsworth & VanLabeke, 2004; Cheng, Lowe, & Scaife, 2001; Hegarty, 2004; Kali & Linn, 2008; Lowe, 2004; Tversky, Morrison, & Betrancourt, 2002) and different ways in which the aforementioned theories can be used to interpret results. For example, using design features that appear to overload working memory can explain why students fail to understand information presented on a screen. Other researchers caution that few studies have established a connection between design features and effective learning. Instead, they observe that it is difficult to conduct well-controlled quantitative research that varies only one design feature for comparative purposes and specifically addresses effectiveness (Ainsworth & VanLabeke, 2004; Dillon & Gabbard, 1998; Geelan, Mukherjee, Martin, & Mahaffy, 2010; Lieberman, Bates, & So, 2009; Rapp, 2007). Clearly, many factors appear to influence students' interactions with visualizations. For example, students' background knowledge (Linn, 2003), the kinds of cognitive load imposed on viewers (highly interactive screens, complexity of the visualization) (Chandler, 2004), students' ability to recognize salient features of the visualizations (Linn, 2003), and teachers' pedagogical knowledge (Wu, Krajcik, & Solway, 2001) are just some of the factors that influence learning. Lowe (2004) concludes that the use of DLOs is likely happening in advance of adequate research that provides evidence of how students learn from these resources.

Despite these observations, lists of design principles have been generated that researchers believe hold the promise to facilitate learning from digital learning objects (Adams et al., 2008; Liu, Toprac, & Yuen, 2009; Low, Jin, & Sweller, 2009; Kali & Linn, 2008; Mayer & Moreno, 2002; Scheiter, Wiebe, & Holsanova, 2009; Schmidt-Weigand, 2009). Kali and Lynn (2008) use a constructivist perspective to explain that learning science is a process of integrating new ideas with existing ideas—a view they argue suggests design principles for digital learning objects directed at elementary science students. These principles include a) reducing visual complexity, b) helping students identify salient features, c) scaffolding the generation of explanations, d) supporting the creation of self-generated models, and e) using multiple linked presentations. Important in addition to these principles are opportunities for students to learn from each other, inspect their own knowledge, and deliberately guide their own thinking (Kali & Linn, 2008). But identifying design principles has not meant that appropriately designed digital learning objects will result in learning. Researchers caution that problems continue to arise when students are novices in the content domain (Ainsworth & Van Labeke, 2004; Lindgren & Schwartz, 2009; Ploetzner & Lowe, 2004; Roth, 2009), the subject matter is innately complex (Cook, Zheng, & Blaz, 2009; Ploetzner & Lowe, 2004), and when students must relate multiple dynamic models (Ainsworth & VanLabeke, 2004; Rieber, Tzeng, & Tribble, 2004; Tversky, et al., 2002). Clearly, more in-depth exploration is needed to shed light on the process of interpreting and understanding scientific models and information presented in digital learning objects and how this process may be linked to design elements (Low et al., 2009; Scheiter et al., 2009).

### *Using Digital Learning Objects to Teach Chemistry*

Some researchers, working mostly at secondary and post-secondary levels, have explored how students interact with digital learning objects designed to promote their understanding of chemistry concepts. These researchers tend to recognize the potential for DLOs to make the unseen world visible (Gustafson, Shanahan, & Gentilini, 2010), portray particle movement (Donovan & Nakhleh, 2007), connect the observable properties of matter with particle behaviour (Ardac & Akaygun, 2005; Russell et al., 1997), and make information more memorable (Mayer & Anderson, 1991).

Studies of secondary students using various forms of technology to learn chemistry (interactive computer visualizations addressing topics such as dynamic equilibrium, intermolecular forces, and thermochemistry) suggest that some students taught with chemistry DLOs show greater conceptual development than those taught without DLOs (Geelan et al., 2010; Wu, Krajcik, & Solway, 2001), and a better understanding of the molecular state of substances (Ardac & Akaygun, 2004) and chemical change (Ardac & Akaygun, 2005). A study of post-secondary students working with web-based tutorials, however, reports that the tutorials did not affect students' conceptual understanding but were still viewed favorably by students (Donovan & Nakhleh, 2007). Other studies report that students viewing a computer simulation had an increased understanding of particles (Williamson & Abraham, 1995), and students showed a decrease in misconceptions about particles (Russell, et al., 1997).

### *Summary*

Clearly, research identifies many challenges for curriculum developers, elementary teachers and students, and digital learning object designers interested in supporting complementary learning at both the observable and particle levels. Curriculum developers need to identify properties of substances and concepts about particles that will help students make necessary connections between the observable and particle levels. Teachers need to develop knowledge about particles and consider how a variety of teaching strategies may support students' understanding. Students need to be willing to think about explanations that may challenge their imaginations and see a payoff for doing so. Digital learning object designers are faced with drawing from studies that show positive, negative, and inconclusive results for the use of technology—a situation suggesting that the interaction between students and DLOs is an area in need of much research.

Many questions remained for our study. Would elementary students be able to construct a beginning understanding of particles when these ideas represented a different way of thinking about the observable properties of matter that had so long been the focus of their school years? Would they be able to understand the importance of using models to portray particles and be able to discern the strengths and limitations of these models? What design features should be incorporated into the DLOs? Would the DLOs help or hinder the students' understanding of particles? We hoped this exploratory study would provide tentative answers to these questions and assist in providing guidance for future studies.

## DESIGN

### *Objectives*

The study spanned four years and yielded both a theoretical framework and several sets of tested resources to support Grade 5 students (and their teachers) to understand the nature of models and the particle nature of matter. Although different years featured different resources (versions of print resources and digital learning objects) that were piloted in different contexts (science centre versus regular classroom contexts), the overall intent was to explore the following questions:

1. What are Grade 5 students' views of the nature of models?
2. What are Grade 5 students' views of the nature of matter?
3. Is there a relationship between students' views about the nature of models and their views of the nature of matter?
4. What are the pedagogical implications of using digital learning objects to help introduce students to the nature of models and matter?

### *Data Analysis*

Similar to approaches described in previous work (Gustafson, Shanahan, & Gentilini, 2010), data analysis began with a detailed reading of students' written responses to survey and worksheet questions and a careful examination of their drawings. Attention was paid to the students' initial ideas about models and particles and whether or not these ideas changed in any way during their participation in project activities. Categories of understanding about models and particles were informed by those proposed by other researchers (Grosslight, Unger, Jay, & Smith, 1991; Kozma, 2000; Nakhleh & Samarapungavan, 1999) and ideas that emerged during analysis (Gustafson, Shanahan, & Gentilini, 2010). Interpretive validity was established through an audit process (Creswell & Miller, 2000). Once the analytical cycle was completed by one researcher, another researcher read the data and examined the analysis. The focus of this internal audit was on whether the categories and interpretations were supported by the students' written responses and drawings. Teachers' written feedback and anecdotal records compiled by the research team were used to set the context for study data. Correspondence between teachers and researchers to share study interpretations acted as a member check and assisted in validating study findings (Creswell & Clark, 2007).

### *Teaching Resources*

In Year 1, we created and piloted a print resource entitled Understanding Models in Science (Gustafson, Shanahan, Gentilini, Mahaffy, & Martin, 2007). This resource featured lessons in which students considered the nature of models and the particle nature of matter. Students' interactions with these lessons were used to inform the design of print and digital resources developed in subsequent project years.

In Year 2, we developed digital learning objects that could support students' understanding of the nature of models and the particle nature of matter. As DLOs were reviewed by the teachers and piloted with students, insights into what proved helpful or challenging were used to modify the design and content of subsequent objects. All of the digital learning objects were created at The King's Center for Visualization in Science (see http://www.kcvs.ca). The DLOs were produced using Adobe FLASH® and contained a variety of digital resources including images, sound files, and animations. Particle-level animations depicting chemical processes were produced using accurate representations from professional chemistry visualization software (HyperChem® and Odyssey®).

Creating digital learning objects involved revisiting research literature on learning about the particle nature of matter and learning about and through models. DLO text and images were intended to a) acknowledge the role of students' existing ideas on learning and common misconceptions, b) connect to students' everyday life experiences, c) help students revisit concepts within a variety of contexts, d) encourage collaboration, e) be sensitive to the limits of working memory, f) acknowledge the diverse reading abilities and keyboarding skills among Grade 5 students, and g) help students notice the models' salient features. We were also aware from our interactions with teachers (e.g., during teacher workshops and teacher conference presentations) that many teachers are uncomfortable with their own understanding of the particle nature of matter and that some shared the same misconceptions research shows are held by students. Therefore, final versions of DLOs included Teacher Notes that featured background subject matter knowledge, a student worksheet that mirrored questions appearing on DLO screens, and a complete script of the DLO text.

These considerations led to incorporating into the construction of the final version of DLOs a variety of design features intended to support the students' understanding of models and particles (see Table 10.1).

Decisions also had to be made about what concepts should be included in the teaching resources. In the end, we wanted the students to gain some insight into how ideas about particles could be used to explain the observable properties of matter and to understand that all models used to introduce these ideas had strengths and limitations. We decided that prior to using models to present particle concepts we would first need to introduce ideas about the nature of models. In this way, we hoped students would be able to use their knowledge about models to engage in more sophisticated thinking about concepts represented in a variety of particle models (see Chapter 9 for discussion of students' thinking about the nature of models).

In the following sections, we present a selection of study results intended to show students' thinking about the particle nature of matter.

*Table 10.1. Examples of Digital Learning Object Design Features Related to Research-based Considerations*

| *Research Consideration* | *Examples of Related DLO Design Features* |
|---|---|
| Existing ideas influence the construction of understanding | Text-only screens asking students to record and discuss their existing ideas. Screens that addressed common misconceptions. |
| Using familiar contexts helps students make connections | Animations of opening a can of pop, baking cookies, and parachute jumpers. Static images of building blocks, laundry on a clothesline, glow sticks, and pancakes. |
| Important to revisit concepts within a variety of contexts | Using text, images, and animations in many modules to revisit the idea that everything is composed of small, unseen particles. |
| Collaborative conversations aid the construction of helpful ideas | Text screens requiring students to work with a partner and draw, talk, and write about ideas. |
| Limits to working memory necessitate checking for understanding prior to introducing additional concepts | Using text-only screens and colour to emphasize important concepts. Inserting audio and movement only when necessary. Sometimes requiring correct responses before advancing to the next screen. Gradually introducing some text through successive clicking. Including summary questions and concepts. |
| Classrooms include students with diverse abilities | Requiring only click and drag, and point and click keyboarding skills. Sometimes including an audio file of screen text. Allowing students to work at their own pace by inserting forward and back arrows on each screen. |
| Need to help students recognize salient features of models | Text advising students to watch closely or to watch animations a second time. Inserting questions related to salient features. |

## TEACHING ABOUT THE PARTICLE NATURE OF MATTER

Particle concepts featured in most of the project's print and digital resources included: a) particles are too small to see, b) there are spaces between particles, c) all matter is composed of particles that are in constant motion, and d) the arrangement and movement of particles helps explain the observable properties of matter.

The first three years of the project featured a variety of approaches to introducing students to particles. In Year 1, we focused on the Grade 5 Alberta science curriculum and how particles could be linked to existing learning expectations and common classroom activities. In Years 2 and 3, the scope and sequence of particle concepts was driven by visits to a local science centre and the kinds of activities included in the centre's chemistry program. By Year 4, we used information gathered in previous years to design six interactive DLO modules that could be integrated into regular classroom teaching. These modules reflected our best ideas at the time for how to introduce and sequence particle concepts. In the following, we describe results with a Grade 5 classroom.

### *Existing Ideas about Matter*

Prior to viewing the six DLO modules, students completed a survey in which they recorded their existing ideas about matter. On the survey, students observed pictures of a pop can (solid), glass of water (liquid), and an inflated balloon (gas) and were asked a) what they knew about solids, liquids, and gases; and b) to explain whether these forms of matter were made of one big piece of material or something smaller. The great majority of students shared helpful ideas about the observable properties of matter (e.g., “Solids are hard”, “You can pour liquids”). Depending on the state of matter, about half of the students added that matter was made of something smaller. Of these students, some wrote ideas that could be helpful in understanding the modules (e.g., “”Solids are made of unseen particles”, “Solids are made of something smaller but tightly packed”, “Liquids are made of a bunch of moving particles”, “Gases are made of small molecules that are far apart so therefore they float”, “Liquids are made of molecules that are spread out more”). Other students had ideas upon which it was more difficult to build understanding (e.g., “”Gas is made of something smaller because we breathe in piece by piece”, “”Solids are made of hard particles”). We speculated that because about half the students already wrote about how matter was composed of something smaller, most would have little difficulty going along with the modules’ assertions that everything was composed of small, unseen particles. What conceivably could present more of a challenge was noticing salient features of multiple particle models intended to show differences among solids, liquids, and gases and connecting the particles to the observable.

After completing the survey, students then viewed ideas about the nature of models in Module 1 (see Chapter 9 for discussion of students’ Module 1 and 2 ideas about the nature of models), and in Module 2 were introduced to the idea that believing in small, unseen particles would help to explain the observable properties of solids, liquids, and gases.

### *Noticing Particle Spacing and Movement*

Module 3 began with asking students to recall how solids, liquids, and gases differed. Although half of the students wrote how various observable properties helped to distinguish among the three states of matter, the other half attempted to incorporate ideas about particles into their answers (e.g., “Particles in solids are close and vibrate”, “Particles in liquids are further apart”, “Particles in gases are spread out”). The teacher speculated that these helpful ideas about particles were likely the result of a variety of classroom experiences. In a previous year, these students had discussed small, unseen particles within the context of a weather unit.

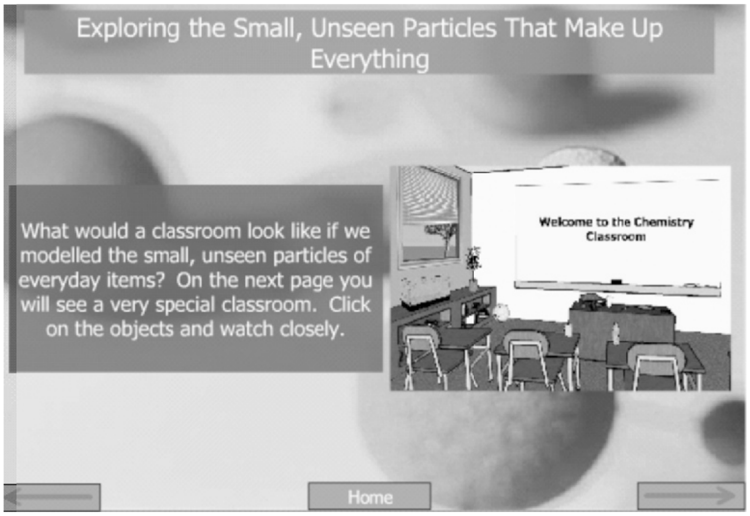
Also, prior to viewing Module 3, the students discussed the seeds-in–a-jar model; participated in a body-movement model of solids, liquids, and gases; constructed Molymod® models of common molecules; and reviewed the three physical states of water.

Students then proceeded to view Module 3 screens in which they were reminded that a) solids, liquids, and gases were types of matter; b) the properties of matter could be explained by thinking about small, unseen particles; and c) models such as those viewed in Module 2 were helpful for showing that big things were composed of smaller things. These reminders were meant to foreshadow the Virtual Classroom DLO now embedded in Module 3 (see Figure 10.1).

The Virtual Classroom DLO allowed students to click on familiar classroom objects to view dynamic, coloured, spherical models of particles that composed the object and read some explanatory text (see Figure 10.2). The overall intent was to help students understand the theory that everything was made of small, unseen particles that featured different spacings and movements.

After viewing a variety of objects in the Virtual Classroom, a subsequent screen asked students to record objects from their own classroom that were made of small, unseen particles. Most students identified solid objects (likely because these were most common and visible) with some simply writing “everything”.

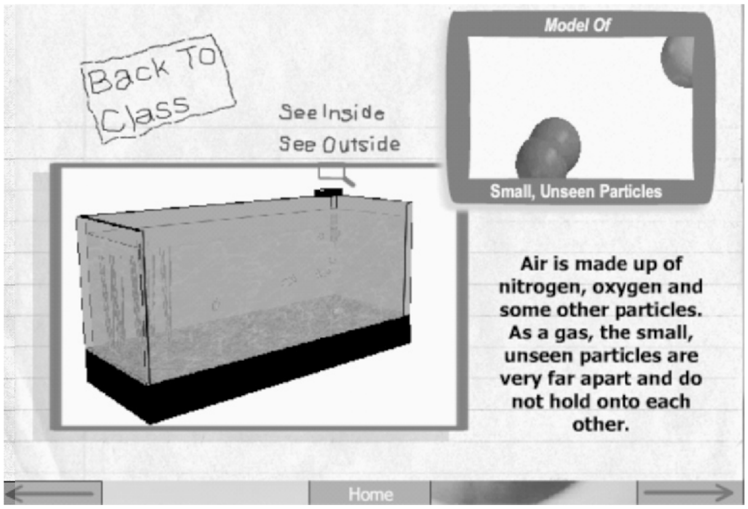
In the Virtual Classroom DLO, one clickable screen object was a plant. We included a plant as other researchers had reported that students could confuse cells with small, unseen particles—an outcome that likely reflects difficulty with scale as well as with textbook explanations that plants and animals are made of very small,



Exploring the Small, Unseen Particles That Make Up Everything

What would a classroom look like if we modelled the small, unseen particles of everyday items? On the next page you will see a very special classroom. Click on the objects and watch closely.

*Figure 10.1. Screen capture from Module 3 showing the title page of the Virtual Classroom DLO.*



Air is made up of nitrogen, oxygen and some other particles. As a gas, the small, unseen particles are very far apart and do not hold onto each other.

*Figure 10.2. Screen capture from Module 3 Virtual Classroom showing information accompanying a clickable screen object.*

microscopic cells. To explore whether students understood that living things were also made of small, unseen particles, the Module 3 worksheet included a question asking students to record what they would have seen if they had been able to click on a person. Three of the twenty-two students wrote that they did not know. Another three wrote that they would see solids, liquids, gases, blood cells, muscles, and bone—responses that did not explicitly refer to small, unseen particles. The remaining students (16/22) provided answers that included the idea that people were also made of small, unseen particles (e.g., "You would see a bunch of particles", "Vibrating particles", "Solids, liquid and gas particles"). These answers showed that for many of the students, the idea that everything was made of particles was being applied to all things.

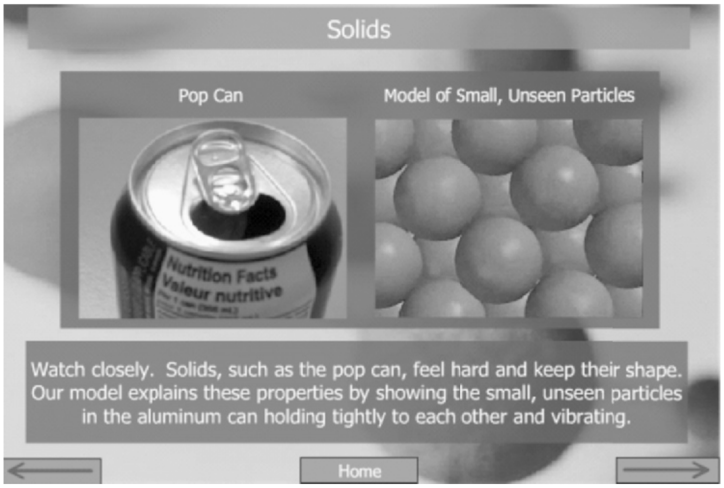
Module 3 concluded with a variety of screens intended to explore students' understanding of the spacing and movement of particles constituting solids, liquids, and gases. On one screen, students had to click and drag particle models of solids, liquids, and gases to their correct place on a pop can. All students were able to successfully complete this task but only 7/22 students wrote about using spacing or movement as criteria for making the matches (e.g., "Liquids are closer", "They vibrate"). Five students simply wrote they recalled the correct matches from the module. Other students wrote "because they matched", and eight students rationalized their matches by referring to some observable property (e.g., "because solid takes the shape of the container", "because pop is a liquid", "because air is a gas"), or by describing the constituents of matter (e.g., "air is made of nitrogen", "pop has carbon dioxide"). For this question, it is difficult to conclude what criteria students were using to distinguish among solids, liquids, and gas. For example, is writing, "because they matched", an indication that this student noticed the importance of particle spacing and movement? And does the response, “because air is a gas”, suggest that this student noticed that gas particles making up air were widely spaced?

### *Connecting the Observable to the Particle*

Three Module 3 screens provided students with dynamic particle models juxtaposed with common images of solids, liquids, and gases. Accompanying text explained how the model could help explain observable properties (see Figure 10.3).

Text appearing on these three screens appeared after students were given a few seconds to view the dynamic images. Questions on a subsequent screen reminded students that they were viewing models of particles and that real particles did not have the colours and shapes depicted on previous screens. Students were also told that the spaces between particles were empty spaces containing nothing. Another screen summarized module concepts: a) everything is made of matter, b) solids, liquids, and gases are types of matter, c) small, unseen particles make up all matter, d) models help us picture small, unseen particles, and e) the arrangement and movement of small, unseen particles can help explain the properties of solids, liquids, and gases.

Three concluding screens presented students with dynamic particle models of solids, liquids, and gases meant to portray differences in particle spacing and movement. For each screen, students were asked to identify the state of matter portrayed, provide a reason for their choice, and describe what it would feel or look like. Every student was able to correctly identify the state of matter portrayed by the particle models but criteria used to inform identification varied among students (see Table 10.2).



Watch closely. Solids, such as the pop can, feel hard and keep their shape. Our model explains these properties by showing the small, unseen particles in the aluminum can holding tightly to each other and vibrating.

*Figure 10.3. Screen capture from Module 3 showing a solid pop can juxtaposed with a dynamic particle model of the solid.*

*Table 10.2. Number of Students Identifying Dynamic Particle Models of Solids, Liquids, and Gases in Module 3 by Criteria of Identification.*

| | *Number of Students (N = 22)* | | | |
|---|---|---|---|---|
| *Criteria* | *Solids* | *Liquids* | *Gases* | *Sample Student Responses* |
| Particle spacing and movement | 8 | 8 | 10 | “Close together and vibrating”, “Spread out and moving fast”, “Move freely past each other and hold less tightly” |
| Particle spacing only | 8 | 3 | 4 | “Close together”, “More spread out”, “Closer than solids” |
| Particle movement only | 0 | 2 | 3 | “Moving fast”, “Wandering in their own area” |
| Number of particles | 0 | 1 | 2 | “Not many particles”, “There are lots” |
| Other | 6 | 8 | 3 | “I saw it in the module”, “It looks like a solid”, “It is like air”, “It is the last one left to match”, “The shape” |

For each state of matter, more than half the students wrote that spacing and/or movement were criteria that informed their selection. We also speculate that some of the students categorized as ‘other’ were using similar criteria to identify states of matter. For example, writing that they “saw it in the visualization’ does not preclude their using spacing and movement to categorize matter. Having categorized the particle models, many students (13-16/22 depending on the state of matter) correctly described the observable properties of the particle models (e.g., “It would feel hard”, “It would have a fixed shape”, “It would feel wet”, “It would feel like air”). Only a few (6/22 for each state of matter) showed difficulty with identifying the observable properties of the particle models (e.g., “[The solid particle model would feel] like nothing because they are so small”, “[The solid particle model would feel] like bouncy balls moving fast”, “[The liquid portrayed in the particle model would look] like blue and different colours”).

The teacher asked students to think about how some matter is made up of different particles (e.g., air is composed of nitrogen, oxygen, carbon dioxide, and water vapour particles), while other matter is composed of only one kind of particle (e.g., pure water is composed of water particles). Although she did not emphasize particle movement and spacing, these activities were useful for revisiting how everything was made of particles and that matter could feature the same or different particles.

Although Module 4 featured ideas about physical change, the beginning screens asked students to record what they could recall about the different arrangements and movements of small, unseen particles in solids, liquids, and gases (see Table 10.3).

*Table 10.3. Number of Students Recalling Criteria about Particles Used to Distinguish Among Solids, Liquids, and Gases in Module 4*

| | *Number of Students (N = 21)* | | | |
|---|---|---|---|---|
| *Criteria* | *Solids* | *Liquids* | *Gases* | *Sample Student Responses* |
| Particle spacing and movement | 15 | 19 | 18 | "Close together and vibrating", "Move fast and freely", "Move fast and collide" |
| Particle spacing only | 2 | 0 | 1 | "Close together", "More spread out" |
| Particle movement only | 2 | 2 | 2 | "Moving fast" |
| Other | 2 | 0 | 0 | "There is no movement" |

These data show particle spacing and movement to be the main criterion to distinguish among solids, liquids, and gases. In order to support the ideas that movement and spacing were critical concepts, students were able to rollover the screen question to once again read about particle movement and spacing in solids, liquids, and gases. We did not rule out, however, that some students could have accessed the rollover answers prior to completing the worksheet question resulting in biased data. Be that as it may, worksheet answers showed many students' willingness to write about the importance of movement and spacing—ideas important to understanding Module 4's focus on physical change.

The post-study paper-and-pencil survey asked students to explain pictures of static, spherical particle models juxtaposed with common examples of states of matter (see Figure 10.4).

Although the pictures did not portray particle movement as in the DLO modules, we hoped students would be able to write about the relationship between the images and refer to how particle spacing was at least one criterion that helps to identify states of matter. As discussed earlier in this chapter, students' explanations made little reference to the fact that the particle image was a model. Their answers, however, contained many useful ideas about particles with only a few students continuing to be challenged by the concepts underpinning the images (see Table 10.4).

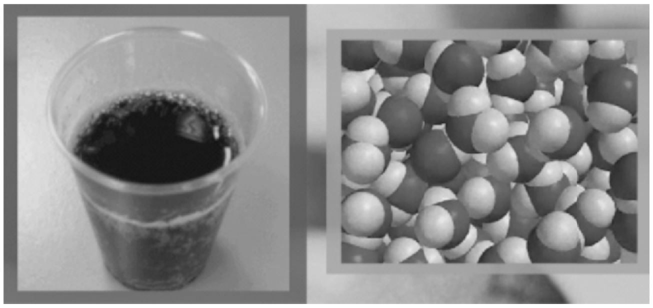


*Figure 10.4. Post-survey picture of liquid pop and a static particle model portraying a liquid.*

Table 10.4 shows that the great majority of students had scientifically sound ideas about the images. Over half used ideas about movement and/or spacing to explain the particle models and many wrote about connections between the observable and the particle. Over half the students (14/21) included the idea of movement in at least one of their responses despite the fact they were viewing a static representation. For these students, concepts about particle movement were durable ideas now being used despite the pictorial models' affordances. Asking these students to generate and explain their own pictorial models would have been particularly intriguing as it appeared many now had sufficient conceptual understanding extending beyond static pictorial models. Also, similar to written responses throughout the study, follow-up interviews could have shed insight into all students' thinking. For example, was a student who wrote "the particles on the right show what would be going on in the metal of the pop can" a student who could then talk about what was going on? If so, then Table 10.4 could have shown an even greater incidence of ideas about spacing and movement and how these ideas explained connections between the observable and the particle.

*Table 10.4. Number of Students Providing Various Explanations of Post-survey Particle Images Juxtaposed with the State of Matter*

| | *Number of Students (N = 21*)* | | | |
|---|---|---|---|---|
| *Explanations* | *Solids* | *Liquids* | *Gases* | *Sample Student Responses* |
| Shows particle spacing and movement | 7 | 7 | 8 | "It shows the unseen particles of a pop can that vibrate very close together", "Shows the unseen particles of a liquid that are close and moving", "Particles are spread out and moving fast" |
| Shows particle spacing only | 6 | 1 | 1 | "Particles have spaces between them", "Particles are close together", "It's a model of particles that hold less tightly", "Particles are spread out" |
| Shows particle movement only | 2 | 6 | 2 | "Shows particles sliding over each other", "Particles are moving" |
| Shows relationship between the images | 18 | 14 | 14 | "Shows particles of the pop can", "Picture of the circles vibrating are the small, unseen particles inside the pop can", "Shows balls are particles of the round can", "Shows the spheres that represent a liquid", "Shows particles of liquid", "Bubbles are a gas, spheres are a gas", "Bubbles are a gas of unseen particles" |
| Other | 1 | 2 | 4 | "It's a can of pop", "Shows particles are all around", "This is a glass of pop", "Shows what particles look like", "Water turns to gas and evaporates" |

*Students could provide answers that fit more than one category.

### *Summary*

The idea that everything is made of small unseen particles appeared easy to accommodate with the students' existing knowledge. Opportunities to discuss the particle nature of matter with each other and their teacher, participate in a variety of classroom experiences (e.g., a body movement model of solids, liquids, and gases), and interact with the project Year 4 DLOs all likely contributed to this understanding. Many students used criteria such as particle spacing and movement to distinguish among solids, liquids, and gases showing that they were capable of noticing salient features of multiple representations. Further, many students showed they understood the significance of why we repeatedly juxtaposed a single screen particle model with still or video footage of observable phenomena. Responses showed they worked to relate the observable and particle levels of thinking about chemistry, with some students providing conceptually clear connections (e.g., "The coloured circles are small unseen particles in the pop") and others still in need of more work (e.g., "The particles spread out to form bubbles"). We speculate that expanding data collection to include interviews with the students could have shed further insight into data presented in 10.3 and 10.4 and could possibly have shown that even more students had noticed the importance of particle spacing and movement.

This study provides some insight into the intellectual challenge of learning about particles while relying on models—a challenge that should not be underestimated. Inevitably, there are trade-offs—an emphasis on 'good enough' spherical DLO models to reduce complexity may foster conceptions that particles are spherical or coloured. There may be good reasons, therefore, to explore even more representations. Rigid spheres can convey misconceptions about atom size and the colours of models can be confused with the colours of substances. 'Fuzzy balls' (Wright, 2003) as complementary 'good enough' representations might help in addressing these conceptual challenges, and might be a feature of our future work on models appropriate for elementary students.

This work with elementary students also has bearing on learning progressions about the nature of matter at the symbolic, particle, and observable levels. We are aware of the danger posed by naïve realist views of the particle nature of matter and that single representations may lead to misconceptions later on that are hard to undo. Our findings suggest that it may be valuable to address two features: (a) the need to overtly address the nature of models when introducing the particle level of matter to elementary students, and (b) the value in using multiple representations of 'good enough' models to anticipate the tendency of young learners to settle on naïve realist views when seeing visual representations of coloured spheres.

## CONNECTIONS AND CONCLUSIONS

From additional work with secondary school science students and teachers and first year university students, we are aware that the distinction between observable evidence and particle-level models to explain that evidence is often blurred. For example, textbook explanations at both of these levels sometimes make statements such as 'carbon atoms are $sp^3$ hybridized' to explain observations about the geometry of carbon atoms in molecules such as methane. In keeping with the approach taken with elementary students, we believe it is more helpful to present evidence of phenomena *before* the theories and then use 'good enough' models (Millar, 2005) to explain that evidence, rather than introducing principles first to explain phenomena encountered later. This approach can help more advanced learners of chemistry continue to see models as human constructions to explain facts, rather than as the facts. This approach has informed the development of a learning resource for first year university students who are introduced to various complementary 'good enough' models such as Lewis structures, hybridization, and molecular orbital theory to explain observable data such as atomic connectivity and geometry, and spectroscopic data (Mahaffy, et al., 2011).

Finally, we emphasize how crucial is the first exposure to chemical substances, physical and chemical changes, and chemical explanations in the conceptual development of young learners. We end with a whimsical thought—perhaps Cardinal Wolsey in the 15th Century had learning progressions about the nature of matter in mind when he wrote: "Be very, very careful what you put into that head, because you will never, ever get it out." We hope that the study described here will be helpful in pointing the way to the care that is needed to support elementary students to progress in their understanding of the matter that makes up their world.

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**Elaine Simmt** is a Professor of Secondary Mathematics Education in the Department of Secondary Education, University of Alberta. Elaine Simmt's interest in mathematics cognition has led her to research learners' and teachers' mathematics knowing in action. Informed by a complexity theories perspective, she works with students and their teachers in classroom settings and teachers in professional development contexts. Elaine is particularly grateful for the opportunity afforded her to work with teachers, graduate students, and colleagues on creating inquiry based learning environments.

**Shannon Sookochoff** is a teacher with Edmonton Public Schools. Shannon is primarily interested in creating tasks for students. She values group interaction in the problem-solving process and looks for tasks that are variable-entry and open-ended. Shannon's teacher/research projects have included topics such as radicals and algebra through visual representation, proof and reasoning as a classroom culture rather than unit of study, functions as narrative, and linear systems with emphasis on meaning-making. Shannon is currently exploring the possibilities for social constructivism in distance education.

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