Chapter 8
Towards Generative Images of Science in Science Education

In this chapter, the contributions of the Family Resemblance Approach (FRA) to reconceptualizing the nature of science for science education are visited collectively having been detailed individually relative to particular categories in previous chapters. The following questions are raised: How are the various FRA categories related to curriculum standards? How can science learning be supported in developing understanding of holistic accounts of NOS? It is argued that the FRA categories bring coherence to the content of NOS in the science curriculum when coupled with effective teaching strategies. Having proposed in previous chapters specific visual tools to ease memory, conceptualization and communication of the FRA categories, we now refer to them collectively as the *Generative Images of Science* (GIS) to emphasize their pedagogical utility. The FRA and the GIS heuristics are applied to example curriculum standards. In concluding the book, further contributions of the FRA to research and development in science education are explored and some recommendations are offered.

8.1 Introduction

So far in this book, the Family Resemblance Approach (FRA) to the characterization of science has been expanded in order to illustrate its potential for applications in science education. By so doing, it has been argued that a new perspective on NOS can provide a platform for developing a holistic and a more inclusive model of science for science teaching and learning. A particular feature of the approach has been the formulation of visual tools that can represent various aspects of science. Visualization is stressed due to its potential to create tangible conceptual representations for relatively abstract concepts. The significance of visualization in science teaching and learning has been extensively reported in science education research literature (e.g. Gilbert, 2005; Gilbert, Reiner, & Nakhleh, 2008;

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Johnson-Laird, 1998; Phillips, Norris, & Macnab, 2010; Wu, Krajcik, & Soloway, 2001). In Chap. 2, we have reconfigured the FRA to be represented as a wheel that can be memorable as a comprehensive representation of the various features of science, including the categories that we have generated to supplement those of Irzik and Nola (2014), which were elaborated on in Chap. 7. In Chap. 3, we summarized a simple triangle distinguishing the epistemic, cognitive, and social aims and values of science. In Chap. 4, we proposed the Benzene Ring heuristic to highlight the dynamic nature of the epistemic, cognitive and social components of scientific inquiry. Similarly Chap. 5 offered the ‘gears’ image to illustrate how explanatory consilience is achieved through the coordination of evidence obtained from different methods. The growth of scientific knowledge framework in Chap. 6 provided yet another form of visual representation of the dynamic nature of the growth of scientific knowledge and its forms as theories, laws and models. Chapter 7 presented a pie chart to represent the social and institutional categories of science. The variety of social contexts was displayed in terms of pieces of a pie, each of which claim space in the science curriculum depending on its relevance to the science content covered at a given time. In Fig. 8.1 we bring together the different representations created in each chapter following a theoretical review, which provides the foundation of their coherence, content, and justification. Collectively, we refer now to these images as “Generative Images of Science” (GIS) since each of them has the potential to be extended and embellished, yet have some central aspects of science captured relative to each component of the FRA.

The images are ‘generative’ due to their potential to be unpacked and extended for further articulation both from philosophical and pedagogical points of view. Some of the extensions can include ideas that would illustrate aspects of science in a generic sense while others might be more domain-specific. In either case, the FRA enables the articulation of the issues in the sense of a ‘family’ category. A balancing act is struck between the domain-general and domain-specific aspects of science. In each chapter of the book, we have illustrated how the particular GIS relates to the science curriculum and how each might be potentially used in instruction. Beyond the theoretical articulation, the adaptations of GIS can act as heuristics for teacher

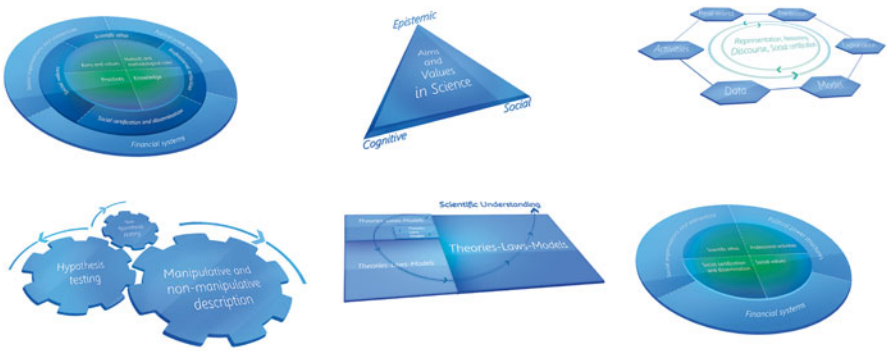


Fig. 8.1 Generative Images of Science (GIS)

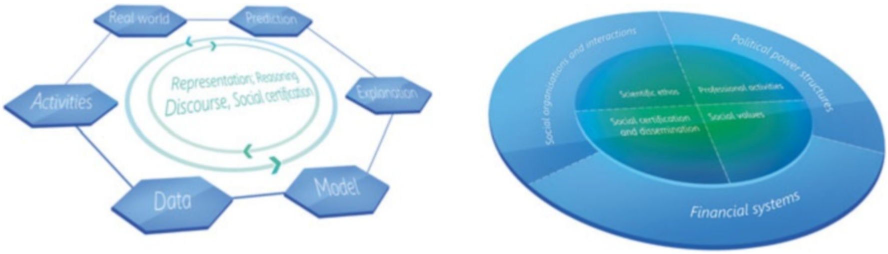


Fig. 8.2 Potential interactions between GIS: scientific practices and social certification

educators, teachers as well as students in capturing a particular aspect of science (e.g. scientific knowledge) as well as science in its overall comprehensive depiction as illustrated with the FRA wheel in Chap. 2. For example, pedagogical adaptations of GIS could potentially act as meta-cognitive tools in communicating to teachers by teacher educators and to learners by teachers the various components of science. GIS could also potentially form a coherent and comprehensive account to formulate assessment criteria such that new assessments can be developed for investigating NOS understanding.

The GIS which are theoretically grounded and justified, are envisaged as interactive components of the FRA model of NOS. In being interactive and dynamic, they possess the potential to generate and highlight new links between them. For example, as illustrated in Fig. 8.2, the Benzene Ring heuristic of scientific practices in Chap. 4 and the pie chart of the social and institutional aspects of science captured in Chap. 7 can be interlinked. The Benzene Ring heuristic illustrates the epistemic, cognitive and social dimensions of scientific practices as being intricately linked in one holistic representation. The links between the different epistemic components are established by the dynamic socio-cognitive processes represented by the electron cloud denoting representation, reasoning, discourse and social certification. The internal ring structure represents the 'cloud' of social processes (including the sociological, cultural and economic dimensions) that anchor the epistemic components. The links between the different GIS can also be made more explicit. For instance, some components, of the social-institutional system discussed in Chap. 7, for instance the idea of "social certification", can be directly imported into the articulation of the ways in which scientific practices like modeling operate, for instance through peer review.

In the rest of this chapter, the discussion is grounded in two current curriculum policy documents. The recently published USA-based *Next Generation Science Standards* (NGSS) document is used to illustrate how the FRA relates to these curriculum standards. The discussion articulates areas that match with the new standards and others where no match was found. In this case, supplementary coverage is proposed. The choice of NGSS is justified for two reasons: (1) they have been recently published and in that sense capture current thinking about science education priorities in the USA, and, (2) earlier science education reform efforts in the

USA have tended to influence much of curriculum reform efforts around the world. Reference is also made to the *Science: Programme of Study for Key Stage 4* (DfE, 2013) from England to illustrate how FRA ideas work with another curriculum policy that is structured differently. The readers could find the FRA analysis of sample curriculum policy documents useful enough to motivate them to apply a similar analysis to documents that are of immediate relevance to them. So our purpose is not to provide an exhaustive overview of how the FRA apply to curricula internationally but rather to illustrate how the FRA can inform the analysis of science curriculum goals.

8.2 Educational Applications of FRA and GIS

How can the FRA and GIS be used in educational contexts? The question is addressed through a series of illustrations. As a reminder, the 'wheel' with the various categories of science as a cognitive-epistemic and social-institutional system presented in Chap. 2 is the basic image on which the other images are developed. In other words, aims and values of science, scientific practices, methods and methodological rules, knowledge, and social-institutional systems are all embedded within the wheel. Hence Fig. 2.1 is the primary tool on which the instructional applications are based with the potential to unpack the various categories through the other GIS (see Fig. 8.1).

From a curriculum planning perspective, the main task while translating the contents of the 'wheel' to practice is to maintain attention on *all of its different components* when planning units of study. The ideas on the wheel can be addressed at the elementary, middle, and high school levels because they involve reflective thinking on science concepts. Through the wheel, students can ask questions that connect what they are already doing, the methods they are using, and the knowledge they are producing. The time allocated to attending to each category depends on its relevance to the context and content of the grade level and unit. Just as the complexity of science concepts unfolds as students move from primary to secondary schooling, so does the complexity of the ideas about science that can be culled to enrich the learning of these concepts along the FRA categories. In other words, it is possible to select strands of ideas from all of the dimensions of the FRA, as detailed in the previous chapters, in a relevant and developmentally appropriate manner to students of all ages. As long as they are made relevant to target science concepts, there exist, by necessity, multiple strands of ideas in each of the FRA categories that can be brought to bear on the topic (Fig. 8.3).

In connecting elements of the wheel to focus on target science concepts, we reaffirm that we are not advocating a particular curriculum approach. Using a basic science, Socio-Scientific Issues, Science-Technology-Society, history of science or any other framework to guide curriculum development, it is appropriate to apply the components of the wheel that fit in best with the content. The design constraints are determined in part by the science content focus and contextual relevance for students. Both of these areas – the content and the design constraints – work together

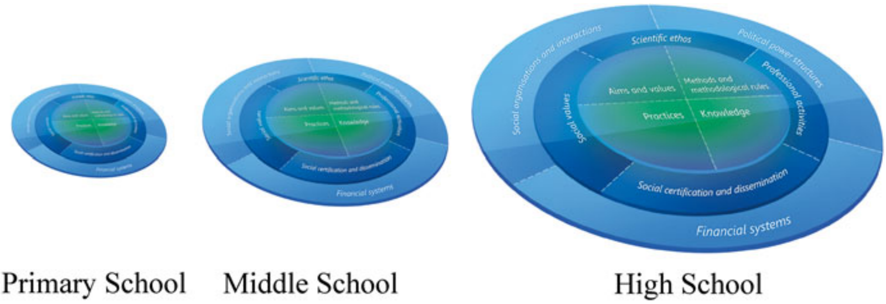


Fig. 8.3 The FRA categories get a larger share of coverage as science concepts increase in complexity across grade levels

to aide the selection of the components that could be emphasized in different parts of the curriculum.

To illustrate the way these theoretical ideas translate into practice, the horizontal and vertical articulation of the FRA components in the science curriculum are considered. As is commonly known among curriculum designers, the idea of "vertical articulation of scope and sequence sets its analytical sight on cross-grade concerns. It is the tool used to build coherence in the educational experience of children during their entire school career" (Kridel, 2010, p. 771). In contrast, in the context of horizontal articulation "…scope and sequence has to do with how school experiences early in academic career will logically and coherently flow into experiences offered later in the year" (Kridel, p. 771).

8.2.1 Vertical Articulation

In a conventional science curriculum, science concepts are articulated vertically by ensuring that basic exposure to these concepts is implemented early in the primary grades and is developed as students progress from kindergarten to high school. This progression can be noted in many curriculum guides and can be followed in Table 8.1 in relation to the topic of "Heredity: Inheritance and Variation of Traits" obtained from the NGSS (NGSS Lead States, 2013a) as an example. Here we see how basic understandings about this topic are developed across the years along a developmental pathway where a deeper understanding is targeted at the high school level.

Since the focus of the discussion is on considering the FRA ideas relative to the science curriculum, we describe how this can be done at the primary and the secondary levels in relation to the specific content of heredity and variation as an example. The process detailed in the following paragraphs can provide some suggestions for curriculum developers on how to engage with nature of science (NOS) based on a FRA model with the same content across stages of schooling.

For analytical purposes, the FRA categories are listed in the same order that was discussed in previous chapters in the book. This should not be interpreted to mean that

Table 8.1 Standards on heredity: inheritance and variation of traits, based on the NGSS (NGSS Lead States, 2013a)

K-2	Elementary school (G. 3–5)	Middle school (G. 6–8)	High school (G. 9–12)
Heredity: inheritance and variation of traits	Inheritance and variation of traits: Life cycles and traits	Growth, development, and reproduction of organisms	Inheritance and variation of traits
1-LS3-1. Make observations to construct an evidence-based account that young plants and animals are like, but not exactly like, their parents	3-LS3-1. Analyze and interpret data to provide evidence that plants and animals have traits inherited from parents and that variation of these traits exists in a group of similar organisms	MS-LS3-1. Develop and use a model to describe why structural changes to genes (mutations) located on chromosomes may affect proteins and may result in harmful, beneficial, or neutral effects to the structure and function of the organism	HS-LS3-1. Ask questions to clarify relationships about the role of DNA and chromosomes in coding the instructions for characteristic traits passed from parents to offspring
		MS-LS3-2. Develop and use a model to describe why asexual reproduction results in offspring with identical genetic information and sexual reproduction results in offspring with genetic variation	HS-LS3-2. Make and defend a claim based on evidence that inheritable genetic variations may result from: (1) new genetic combinations through meiosis, (2) viable errors occurring during replication, and/or (3) mutations caused by environmental factors
			HS-LS3-3. Apply concepts of statistics and probability to explain the variation and distribution of expressed traits in a population

the ideas should be addressed in the same sequence, but rather that the purpose here is to facilitate systematic comparison across primary and secondary science. Ideally, the questions listed under the FRA dimensions are embedded in investigations.

8.2.1.1 Primary Science Example

Taking the topic of variation and diversity, young children as early as kindergarten explore such questions as: "What are all the living things we can find in a small plot? Are they the same? Are they different?" (Chalfour & Worth, 2006). At this young age, students are typically guided through a number of investigations that include looking for organisms, observing their characteristics, drawing them, then lumping them into broad groups (plants, animals), further examining each group and organizing them into broad categories such as eight legged ones are spiders, six legged ones are insects. In the process of performing observations and discussing findings, the teacher can use the "FRA wheel" (Fig. 2.1) to select which aspects of each of the main FRA dimensions are best to emphasize. Those are then prioritized and embedded strategically in the course of lessons. The main task is to select components from each dimension that best fit in with target science concepts and in ways that enhance student engagement. The following outline provides an example starting point in designing lessons that would cover each of the FRA categories at the primary level.

Aims and values: Focus on accuracy, critical examination, revising convictions, and not harming organisms or destroying plans in the process of observing them (i.e. respect for the environment).

Practices: Focus on reflecting on types of representation, differences in data collection and organization and their affordances, considering the multiplicity of patterns, developing models for grouping organisms, focusing on features of classification models.

Methodology: Focus on elements of observations, what things to look for, the idea that students are engaged in observations and need not manipulate the observed entity. As children engage in the activity they are asked to reflect on the different ways in which they observed it (only their eyes, magnifying lens). They consider how did the use of tools (or not) affect their observation. They speculate on how might a scientist (e.g. botanist, entomologist) observe a similar kind of terrain? What tools would she use to make sense of the findings?

Knowledge: Focus on the structure of the knowledge produced. The teacher would go beyond the answers to the initial questions to ask the students about what was learned, why would this information help them do and how? Why might scientists care to do similar investigations? What happens to the knowledge they come across and how do they use it? How do they coordinate the information they use about biodiversity to arrive at theories?

Social-institutional system: Focus on scientific ethos, professional activities, social certification in relation to ecological issues. How does what students did in class resemble what scientists do? How do scientists establish their findings when examining the same question? Do they change their ideas? Have they always classified things the way the students did? Here things like pharmaceuticals and ecological diversity may come up, even contributing to film making (e.g. http://bugsaremybusiness.com/bio.htm), which children would find fascinating. Issues of biotic diversity and how they affect decisions on land use can be brought in such as building a bridge, or a shopping center and how it might impinge on species diversity (e.g. local cases can be linked to this if deemed appropriate).

8.2.1.2 High School Science Example

Using the topic of genetic variation and diversity, high school students can explore such questions as: How does genetic diversity affect the persistence or decline of a species? What causes genetic variability? How does this variability affect the survival of a species? What solutions can address issues of endangered species? An inquiry into these questions can begin by focusing on the context of humans and later explore them in terms of populations and ecosystems. Students can be guided through a number of investigations that include making observations about what characteristics they share with family members and then with classmates, looking for shared and unique characteristics within family, then discuss their observation about their classmates, and people in the larger society. Students are encouraged to use observations about traits or phenotypes to make claims about genotypes, and explore through multiple simulations and actual data how variation in parent genotypes results in variation in phenotypic and genetic variation in offspring. Eventually this continues on to relating genes to chromosomes, study of genomics and so on. In the process of participating in a myriad of investigations, the teacher can use the FRA wheel (see Fig. 2.1) to select which aspects of each of the FRA dimensions are best to emphasize. As is the case with the previous example, the teacher will find several big NOS ideas that they can choose to emphasize as they go through the unit. The following is an example outline for specifying each category of FRA applied to the topic.

Aims and values: Focus on accuracy of observations, critical examination, revising convictions, and not harming the organisms in the process of observing them (respect for the environment). These aims and values are similar to those covered in earlier grades but can be expanded upon in greater complexity and sophistication.

Practices: Focus on reflecting on their observations, data collection and organization, finding patterns, reflecting on statistical models they for predicting offspring, focusing on the relevance of patterns and anomalies they note in the application of the models.

Methodology: Focus on elements of observations, note the contributions of observations to explanations that are not observable. As they investigate, students reflect on the different ways in which observations in this domain can be done (with and without tools). They consider how scientists use manipulative tools to study the human genome. They compare the methods they used to those used by scientists.

Knowledge: Here the focus could be on the structure of the knowledge produced. Going beyond the scientific knowledge, students explore how the gene concept evolved over time and understand the role of models and theories in shaping knowledge growth. This would lead to a discussion about the assumptions that hindered understanding, and which ones led to major breakthroughs in science and technology.

Social-institutional system: Here the focus could be on scientific ethos, professional activities, social certification, competition among scientists (i.e. personalities) in relation to genetic engineering. How does what they did in class resemble what scientists do, how do scientists get better results? Who owns the genetic code? What societal impact does this topic carry? How does the public use this information? What ethical issues confront research in this area? How does knowing the science underlying genetic engineering help students help them sort through media claims? What financial and political issues does this domain entail? Who owns the knowledge that the scientists produce? Is it public or private property? What aspect of this knowledge is proprietary? What role does the legal system play? What role do citizens play? Can the government limit what can be studied? How does all this discussion affect what you do as a student, consumer of goods (e.g. food, medicine) and as future citizens?

In the case of the topic of heredity and diversity at the high school level, we note that more complexity about the social context can be shared at a much more detailed level than was done in the primary science example. But in both examples, all categories and components of the FRA are included. This sort of coverage can be part of a problem-based learning approach, a socio-scientific issues approach, or a more traditional one. The decision of how to contextualize the FRA categories can be tailored to students' interests and abilities and accommodated with the curricular constraints. The final outcome is that by the time the unit is done, students will have learned substantial science and NOS content. They will have covered a broad range of ideas as they reflected on aims and values, practices, methodologies, models, and wide-range of related social issues. Connections can be made between science and engineering practices, genetics, genomics, genetic engineering, legal issues, public interest, privatizing knowledge through patenting laws. The depth and breadth can be pursued in a number of ways: through group projects focusing on one of these facets, through debates in which a jigsaw strategy is used to redistribute expertise across newly formed 'expert' groups, so on and so forth. There is no shortage of ways to organize or sequence the learning of these principles using historical cases or current local and global events.

8.2.2 Horizontal Articulation

In the previous section, we illustrated how components of the FRA increase in sophistication as science concepts get more complex in moving from primary to secondary school curriculum. In this section, we outline how the FRA categories can be targeted across science topics taught in the same grade level. A similar process can be followed for outlining how the FRA categories can be connected to the content. This shows how the FRA can help maintain a continuity of coverage of NOS themes throughout the school year. This is a matter of great concern to science educators who have often complained about the typical NOS coverage in an introductory textbook chapter that never gets to be revisited again in successive lessons.

As an example, we start with *Science: Programme of Study for Key Stage 4* (DFE, 2013) from England aimed at the age group 14–16. Table 8.2 illustrates how the FRA categories can be mapped to some example topics (ie. cell biology, Periodic Table and energy). We use subtopics from each main topic to produce example descriptions of FRA categories. Figure 8.4 illustrates how systemic inclusion of the

Table 8.2 Articulation of FRA categories across science topics in *Science: Programme of Study for Key Stage 4* (DfE, 2013) from England

Science topic	Cell biology	Periodic table	Energy
Subtopic	*The importance of stem cells in embryonic and adult animals and of meristems in plants*	*Predicting chemical properties, reactivity and type of reaction of elements from their position in the Periodic Table*	*National and global fuel resources, renewable energy sources*
Aims and values *e.g. Empirical adequacy*	Use data on stem cells to determine how they influence embryo development	Use data on the physical and chemical properties of elements to conclude which elements they belong to	Use data on fuel resources and how they provide energy
Practices	Discuss similarities and differences between experiments and simulations performed in class and those done in academic or industrial labs	Generate classifications of elements on the basis of their physical and chemical properties; consider how different classification and arrangements of the elements in the Periodic Table illustrate different trends in properties	Generate classifications on the pros and cons of different energy sources and their risks to environment. Generate representations of data produced by scientists noting aspects of practices that explain differences between communities
Methods	Compare the different methods scientist use to conduct stem-cell research. Discuss manipulative methods, compared to non-manipulative methods	Conduct experiments to compare chemical reactions of different elements e.g. oxidation and solubility in water	Discussion and comparison of energy production techniques based on a range of energy sources like solar, wind and nuclear energy
Knowledge	Consider how stem cell theory fits in with other theories, and how new explanatory models in this area revised our understanding about cell growth and development	Consider the variation between the columns and periods of the Periodic Table and what they indicate about chemical and physical properties of elements	Consider the nature of different sources of energy and compare their efficiency in generating energy
Social-institutional e.g. Economic, ethical	Discuss impact of stem cell research on the health sector, medical field, and personal decisions; ethical issues arising from stem cell research; funding issues (public *v* private) and knowledge ownership	Predict the personal and environmental safety of chemicals and hold institutions responsible for ethical disposal of chemical waste Consider the economic impact of some chemicals (e.g. in food processing industry, in air) on personal and public health	Consider the political and economic interests governing the use of national and global energy resources, investment in researching green energy sources

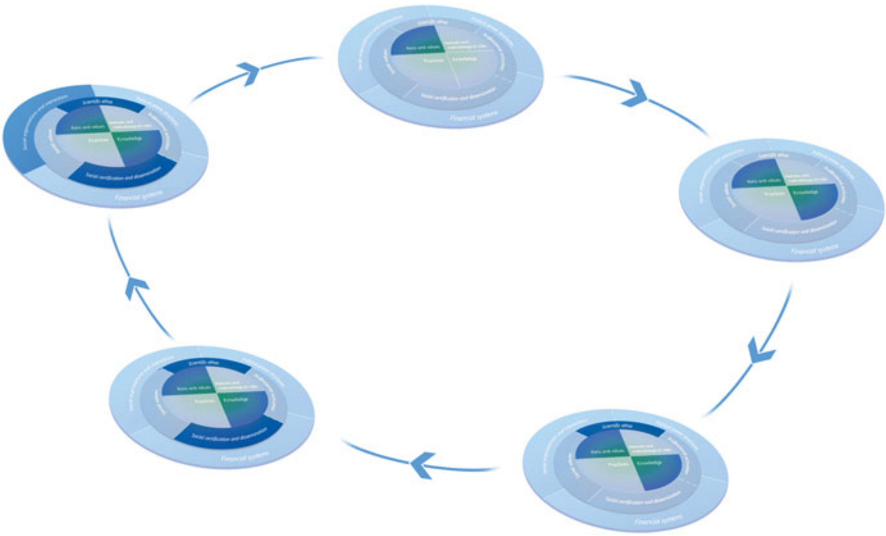


Fig. 8.4 Rotating emphases for unpacking different categories of the FRA within the same science topic or across topics/domains

FRA categories can be accomplished. As seen here, there is no NOS predetermined content that is simply inserted in each row—but there is a category that makes it possible to bring in relevant NOS 'talking points', specifically tailored to the science content. By the time students finish 12 years of schooling that are focused on the multidimensional approach to NOS, students will have amassed a relatively sophisticated understanding of NOS ideas each of which is contextualized and instantiated in disciplinary or multidisciplinary knowledge. They will develop the ability to transfer this information into novel contexts. They will be prepared, for instance, to ask critical questions about methods, justification for claims, values underlying research projects. They will be able to identify ethical issues, guard against gender inequities in science and other fields, and understand the economics of funding and proprietary rights. As future citizens, whether laborers, lawyers, teachers or scientists, students will be aware of the ways in which scientific knowledge and reasoning can empower them to question claims, verify information, and make informed decisions.

In summary, the ideas implied by the FRA categories are infused into the curriculum while taking into consideration the developmental, cognitive and instructional sequences. The movement from different emphases as the wheel cycles through the curriculum could be conceived (a) within a particular grade level, i.e. where the wheel is introduced and gets unpacked in detail to a select set of subcomponents as the school year unfolds; (b) across grade levels, i.e. where subject matter knowledge gets specialized allowing for the inclusion of additional FRA categories. In either case, the wheel model provides a visual and dynamic representation of the curricular components as well as the instructional processes. Overall, the FRA wheel model and its embedded GIS are comprehensive, dynamic, flexible, and fluid. They can be integrated meaningfully into the science curriculum not only across schooling from kindergarten to high school level but also potentially in post-secondary science education.

8.3 FRA, GIS and Curriculum Policy Documents

In discussing the progressive iterations of GIS in schooling, we have advanced the position that a comprehensive account of science (i.e. including the epistemic, cognitive and social aspects) need to be presented to students in a holistic fashion across all grade levels. It was also noted that particular aspects might need to be 'suppressed' while others are emphasized at different grade levels. This position may at times be at odds with some curricular policy arguments that advocate particular aspects of science to be taught at particular grades only. For example, *A Framework for K-12 Science Education* (NRC, 2012) in the USA suggests that economic and other connections to science be explored in Honors or AP courses. Our concern in this regard is that by associating particular aspects of science with particular competency levels, the majority of students who choose not to take advanced courses will not get a good understanding of the social context of science. In practice, we acknowledge that it may not be possible or feasible to address every aspect of the FRA at the same depth at each stage of schooling. However, in principle, aspects from each of the FRA categories must be addressed *systemically* so that students do not end up with fragmented or distorted conceptualization of NOS. This is where vertical and horizontal alignment within and across the science curriculum would help maintain coherence.

The alignment of the curriculum with learning and assessment goals is a necessary undertaking. In using the FRA for curriculum planning, it is important to match curricular goals with innovative instructional interventions and assessment forms. Douglas Allchin who has argued for the teaching and learning of the nature of (whole) science (Allchin, 2011) also highlights the significance of designing assessments that are consistent with revised instructional goals. Before turning to the issue of assessment in more detail, example standards from *NGSS* (NGSS Lead States, 2013a) are used to illustrate how the FRA can serve as a framework to investigate science standards.

8.3.1 Example 1: HS-LS3 Heredity: Inheritance and Variation of Traits

In this example, heredity-related standards are examined against the main categories of the FRA to model how NOS ideas can be integrated into these content standards. The "Heredity: Inheritance and Variation of Traits" standard (NGSS Lead States, 2013a, p. 89) includes three main learning outcomes:

HS-LS3-1. Ask questions to clarify relationships about the role of DNA and chromosomes in coding the instructions for characteristic traits passed from parents to offspring.

HS-LS3-2. Make and defend a claim based on evidence that inheritable genetic variations may result from: (1) new genetic combinations through meiosis, (2) viable errors occurring during replication, and/or (3) mutations caused by environmental factors.

HS-LS3-3. Apply concepts of statistics and probability to explain the variation and distribution of expressed traits in a population.

The emphasis in this standard is on asking questions for the purpose of clarifying relationships. The standard focuses on developing evidence-based arguments and the engagement in mathematical thinking through the use of statistics and probability concepts. Students are expected to engage in scientific practices along the lines defined in the vision document (NRC, 2012): ask questions, make and defend claims, and use mathematical thinking. However, understanding scientific knowledge and practices does not guarantee understanding the nature of science. The "connections to nature of science" included in the interpretive section below the standards specify two ideas under "science as a humans endeavor" theme:

- Technological advances have influenced the progress of science and science has influenced advances in technology. (HS-LS3-3)
- Science and engineering are influenced by society and society is influenced by science and engineering. (HS-LS3-3)

The connections to nature of science called for here are too broad to help teachers determine the relationships that should be made between science and technology, and science and society. It will be left to the imagination of curriculum developers to tie these two connections to nature of science to the third standard. The primary learning outcomes expressed in the standards do not *explicitly* include science as a human endeavor (an NOS Category in Appendix H), nor require an understanding of NOS dimensions discussed by the FRA: scientific aims and values, practices, methods, knowledge and science as social systems in science including science as a social enterprise. In other words, it is possible for students to understand the explicitly stated learning outcomes and bypass the meta-level connections with science as a cognitive-epistemic system or science as a social-institutional system. If the learning goals miss a holistic account of science, so will the instruction. If particular aspects of science are not prioritized nor signaled as important or relevant in applying the standards to the curriculum, they will not be assessed.

The HS-LS-3 Standard misses a golden opportunity to address scientific ethical, social, and economic arguments pertaining to the developing technologies, funding and ethical issues in the context of genetic mutations and genetically modified organisms. Genetic modification technologies bring up significant issues that affect personal and societal decisions about safety, cost, social and environmental impacts. They also provide a meaningful context for discussing the role of patents in limiting access not only to the products of those technologies but also to scientific knowledge itself. The standard does not refer to genetic modification technologies of cloning, gene therapy, genetic engineering and selective breeding.

8.3.2 Example 2: From Molecules to Organisms – Structures and Processes

The next example, based on high school life science standards in the NGSS (NGSS Lead States, 2013a), is used to illustrate how individual standards pertaining to this topic can be supplemented with NOS content. Because a NOS meta-cognitive structure is lacking in the current standards, we exemplify in Table 8.3 how the FRA can be used as a tool to guide the selection of appropriate NOS content that complement and enrich the life science standards depicted here. Expressing the infusion statements in terms of learning outcomes provides clarity for instructional and assessment purposes.

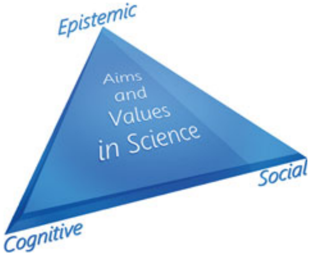
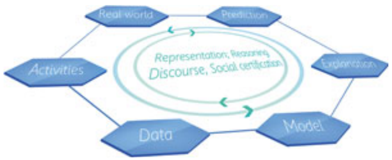
The GIS serve as heuristics or memory aids in searching for NOS content. The example in Table 8.3 illustrates using the FRA as an analytical tool that can be further refined to provide a fine-grained analysis. The comments in the third column of the Table show the results of conducting a systematic content analysis on the target standards conducted to identify NOS connections, strengthen those that are weak, and address those that are absent. For a systematic evaluation or curriculum development purposes, it is useful to study standards pertaining to a given grade band (e.g. K-2, 3–5) to identify missing components and develop amendments. In summary, the FRA and the associated GIS can be 'tweaked' for use as meta-cognitive tools to analyze, evaluate, or reflect on curriculum materials or curriculum policy documents in order to identify if and how different aspects of NOS are being addressed, and help develop a coherent plan for addressing pertinent but missing FRA categories in science curriculum and instruction.

8.4 Potential limitations of the FRA and GIS

The extended FRA categories and the related GIS are intended to provide a multifaceted approach to addressing a range of ideas that impact NOS and its teaching. At the same time, it should be noted that the FRA has a number of potential limitations. These limitations are summarized in relation to approximation, ontology, metaphysics, openness, application and perception of competing goals. In the following paragraphs, each of these issues is discussed to alert the reader about where further work is needed in developing the strengths of FRA.

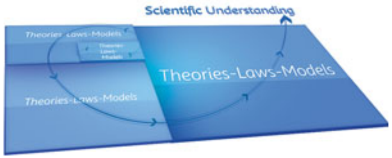
Approximation: The FRA wheel can be used as an instructional model that approximates the components of a complex domain (i.e. science and nature of science). It brings coherence to science content by uniting it around salient FRA categories. The cognitive and developmental aspects of the various categories of science represented in GIS need to be researched by using empirical evidence on teaching and learning such that theoretical rationales for using FRA/GIS in science education are complemented with empirical ones.

Table 8.3 HS-LS1 from molecules to organisms: structures and processes in the NGSS (NGSS Lead States, 2013a)

GIS	Standard HS-LS1	Comments to support FRA infusion
Aims and values 	Not addressed	Several aims and values can be addressed in this context. Focusing on criteria that scientists use to evaluate the strength of evidence can be one aim that could be easily included
		To infuse NOS, add:
		Generate criteria to evaluate and reflect on the quality of data, and if necessary revise criteria for data evaluation
Practices 	*HS-LS1-1. Construct an explanation based on evidence for how the structure of DNA determines the structure of proteins which carry out the essential functions of life through systems of specialized cells*	These learning outcomes involve the design and performance of an investigation, which are components of scientific activities but they fall short of adding the reflective component necessary for discussing the nature of science
	HS-LS1-2. Develop and use a model to illustrate the hierarchical organization of interacting systems that provide specific functions within multicellular organisms	*To infuse NOS, add:*
	HS-LS1-3. Plan and conduct an investigation to provide evidence that feedback mechanisms maintain homeostasis	Consider the nature of representations, particularly in relation to models and modeling. Produce and evaluate different representations. Some of the evaluation criteria generated in Chap. 6 (e.g. projectability, approximation) can be relevant in establishing how models are articulated and evaluated
	HS-LS1-4. Use a model to illustrate the role of cellular division (mitosis) and differentiation in producing and maintaining complex organisms	
	HS-LS1-7. Use a model to illustrate that cellular respiration is a chemical process whereby the bonds of food molecules and oxygen molecules are broken and the bonds in new compounds are formed resulting in a net transfer of energy	

(continued)

Table 8.3 (continued)

GIS	Standard HS-LS1	Comments to support FRA infusion
Methods 	*HS-LS1-3. Plan and conduct an investigation to provide evidence that feedback mechanisms maintain homeostasis*	This learning outcome can be supported from an NOS perspective by discussing a *range of relevant methods* for designing appropriate investigations
		To infuse NOS, add:
		Evaluate the pros and cons of different investigations. Determine what methods are likely to produce stronger evidence. Compare to methods and tools to those of scientists
Knowledge 	*HS-LS1-5. Use a model to illustrate how photosynthesis transforms light energy into stored chemical energy*	This learning outcome supports student use of existing models, or constructing and revising model. It misses the metacognitive components that link their work with models to the work of scientists
	HS-LS1-6. Construct and revise an explanation based on evidence for how carbon, hydrogen, and oxygen from sugar molecules may combine with other elements to form amino acids and/or other large carbon-based molecules	*To infuse NOS, add:* Reflect on the nature of models. Compare students' models to current or historical models. Discuss the bases on which these models can be, or have been, evaluated
	HS-LS1-7. Use a model to illustrate that cellular respiration is a chemical process whereby the bonds of food molecules and oxygen molecules are broken and the bonds in new compounds are formed resulting in a net transfer of energy	

Social-institutional system 		
Professional activities	Not addressed	*To infuse NOS, add:* Examine scientific literature and prepare presentations to communicate findings or defend recommended models
Scientific ethos	Not addressed	*To infuse NOS, add:* Discuss the rights of human subjects when obtaining genetic material
Social certification and dissemination of scientific knowledge	Not addressed	*To infuse NOS, add:* Share and debate written/oral presentations. Compare process to communities of scientists
Social values	Not addressed	*To infuse NOS, add:* Explore ways in which social utility as a value has contributed to this line of work.
Social organization and interaction	Not addressed	*To infuse NOS, add:* Discuss the variety of scientific networks working on DNA research
Political power structures	Not addressed	*To infuse NOS, add:* Discuss relevant cases that illustrate gender bias and political influences on genetics research
Financial systems	Not addressed	*To infuse NOS, add:* Discuss cases that illustrate the financial dimensions of genetics research

Ontology: A potential limitation is that the GIS are based on cognitive, epistemic and social- institutional dimensions of science, and does not focus on ontological assertions. However, in the Benzene Ring heuristic, we have referred to a real world that scientific practices deal with. Aspects of GIS can be used to raise discussions about ontological assumptions.

Metaphysics: One important aspect of nature of science pertains to its metaphysical assumptions which were not explicitly and directly addressed in this book. Three metaphysical assumptions are highlighted by Dilworth (2007): (a) the principle of uniformity of nature, (b) the principle of substance, and (c) the principle of causality. FRA does not explicitly deal with Dilworth's metaphysical assumptions. The NGSS include a statement that falls under Dilworth's first principle. It states that "scientific knowledge assumes an order and consistency in natural systems" (NGSS Lead States, 2013b, p. 6). We believe that science education should instill in learners some awareness about important assumptions that form the foundations of science.

Openness: The FRA has a generative nature that we consider to be one of its strengths as well as its limitation. In the same way that this generative nature can inspire creative means for enriching teaching and learning, it is possible that some future depictions extend the features of science to dimensions that we do not yet anticipate nor endorse. Hence FRA is inherently prone to exploitation and distortion. We suggest that however the FRA categories are extended, the best policy is to use an evidence-based approach to their articulation akin to the way that we have drawn from the research literature on philosophy of science.

Application: The variety of FRA categories and the related GIS serve as metacognitive tools that are dependent on a relatively good understanding of the cultural studies of science. While the GIS provide a reminder of which components to include within each FRA category, the application of the images demands careful research and selection of supplementary materials (such as historical episodes and methodological case studies) that are inherently specific to the science content.

Perception of competing goals: The FRA must not take on a life of their own. FRA categories do not compete with but rather serve broader science education goals, such as the holistic representation of science in school science. However the FRA runs the risk of being misperceived as placing unreasonable demands on the curriculum. The optimal use of FRA and the related GIS is heavily dependent on integration with core science concepts. These concepts become the context where reflective consideration of scientific values, practices, methods, knowledge and social processes can take place.

The implementation of the FRA can be facilitated by knowing what GIS can and cannot do, and considering the ways in which the strengths can be optimize and the limitations minimized. Despite the mentioned potential limitations, the FRA provides a fruitful reconceptualization of NOS in science education. It also provides innovative avenues for future research. For example, investigating the extent to which students' understanding of NOS might improve given a holistic and visual account of science is a line of work that is at the heart of the empirical validation of the proposed FRA framework.

8.5 Recommendations

The previous sections illustrated multiple ways in which the FRA and the GIS can be used as tools to articulate NOS ideas vertically and horizontally across the curriculum, and to analyze curriculum standards documents. In this section, some recommendations for teaching, teacher education, curriculum and assessment are made in order to support the implementation of FRA categories in school science. We are mindful of the fact that the reconceptualized version of NOS is a theoretical account and hence, the recommendations are meant to be guidelines that can help inform researchers who are interested in pursuing future empirical studies.

8.5.1 Teaching

The FRA and the related GIS are likely to be effectively taught when teachers couple them with evidence-based science learning strategies. Some strategies that have been extensively researched include the use of practical inquiries, group discussions and presentations, role play, questioning, differentiation and peer assessment (e.g. Abell & Lederman, 2007; Gabel, 1993; Palincsar, Magnusson, Collins, & Cutter, 2001). Model-based inquiries immerse students in investigations where they collect, interpret and present data to generate scientific explanations, models and arguments. Group discussions and presentations engage learners in the social and cultural practices of science through communication, dialogue and public display of ideas based on evidence. Role play enable students to evaluate different points of view including a range of explanations for a particular phenomenon; it engages learners in the generation and application of criteria for discriminating scientific ideas from other ways of knowing. Differentiation provides the opportunity to tailor the science content to the needs and abilities of individual students. Peer assessment promotes student voice in the classroom and creates a context for learning among peers. Such strategies represent a sample of teaching approaches that promote active communities of learning and personal engagement with science. Furthermore, such strategies model ways of acting, thinking and communicating that form the fabric of the culture of science as a discipline. For example, scientists themselves argue about different hypotheses, theories and models; science cultures tend to have a range of expertise where problems to be investigated are differentiated according to background and interests; professional peer review systems validate and justify the dissemination of scientific knowledge.

8.5.2 Teacher Education

There is a substantial body of literature on teachers' continuous professional development (CPD). The effective uptake of the FRA by teachers will rely on the incorporation of evidence on CPD. Within proposed and researched CPD models, it is widely accepted that learning to teach is not a linear process and that educational change is not a "natural consequence of receiving well-written and comprehensive instructional materials" (Hoban, 2002, p. 13). For teachers' learning to be effective, a more complex view of professional development is required, incorporating professional learning systems. It is widely documented that educational change is complex and takes time (Fullan, 2001), and fundamental and substantial changes could not be achieved within a short period of time (e.g. Erduran & Dagher, 2007). Furthermore, across the world, in the current context of accountability and high stakes assessment, teachers operate within curricular constraints that may be perceived to be incompatible with innovative approaches to teaching and learning.

Supovitz and Turner (2000) argue that high-quality professional development (a) immerses participants in inquiry, questioning and experimentation; (b) is intensive and sustained; (c) engages teachers in concrete teaching tasks and is based on teachers' experiences with students; (d) focuses on subject-matter knowledge and deepen teachers' content skills; (e) is grounded in a common set of professional development standards and show teachers how to connect their work to specific standards; and (f) is connected to other aspects of school change. Effective teacher education however often requires teachers to engage in practices that may not be supported by institutional expectations, for example sharing of teaching resources versus maintaining privacy about them (Spillane, 1999). Apart from teachers experimenting with new strategies, teachers' reflections on their practices are essential part of their learning. However it is difficult to anticipate the extent to which any new professional development initiative would facilitate the process of reflection-in-action, or reframing (Schön, 1987), that results in constructing new pedagogical understanding of NOS.

Nevertheless articulation of teachers' knowledge about FRA will need to be consistent with successful models in teacher education research. For example, Shulman and his colleagues' conceptualization of teachers' subject-matter knowledge in terms of "content knowledge", "pedagogical content knowledge" (PCK), and "curricular knowledge" are significant constructs to apply to the FRA because such application may illustrate what teachers will need to know in order to teach NOS based on a FRA. According to Shulman (1986), "content knowledge" refers to "the amount and organization of knowledge per se in the mind of the teacher", including knowledge of the "substantive structure" and "syntactic structure" of the academic discipline — two terms borrowed from Joseph Schwab (1964). The syntactic structure concept, for instance, can be embellished with a broader framing provided by the FRA. For example, the issue of growth of scientific knowledge as highlighted in Chap. 6 can pinpoint the ways in which knowledge construction mechanisms operate in science. Also named "subject-matter knowledge for teaching", "content knowledge" was subsequently elaborated upon by Grossman, Wilson, and Shulman (1989) as consisting of the following four components: (a) content knowledge—the "stuff" of a discipline; (b) substantive knowledge—knowledge of the explanatory framework or paradigms of a discipline; (c) syntactic knowledge—knowledge of the ways in which new knowledge is generated in a discipline; and (d) beliefs about the subject matter—feelings and orientations toward the subject matter. All of these components of teacher knowledge are directly relevant to applying the FRA categories to teacher professional development. For example, extending the teachers' knowledge base of the social and institutional aspects of science may provide a fruitful territory for teacher educators to consider in relation to how teachers can integrate such aspects into their existing pedagogical repertoires.

8.5.3 Curriculum and Assessment

Throughout this chapter and the previous chapters, we have repeatedly drawn on example curriculum standards to illustrate the relevance and utility of the FRA for curriculum planning and design. Hence the recommendations in relation to the curriculum are situated in each aspect of FRA along with the suggestions on how FRA can help improve the content of the curriculum. As a summary, a FRA can:

1. provide models in developing and implementing teaching units and lesson plans;
2. promote discussion of relevant epistemic, cognitive and social-institutional issues in relation to curriculum content;
3. establish focus for the exploration of historical or contemporary science cases (such as those described by Allchin, 2013), or researching recent news reports, where the cases are relevant thematically and developmentally to the target audience;
4. serve as a point of reference for exploring the content of science topics from as many angles (e.g. epistemic, cognitive, social, cultural, financial) as possible.

The GIS produced in each chapter can be used as starting points for developing more specific assessment tools for use in teacher preparation programs as well as K-12 classrooms. For example, indicators of understanding the aims and values of science can be generated. An example of scientific aims and values reviewed in Chap. 3 is "empirical adequacy". Theoretical accounts of such scientific aims and values can be scrutinized relative to the research evidence on how children use data and evidence in supporting their claims derived from empirical investigations (e.g. Kuhn, 1991). Overall, developing a functional use of the FRA is contingent on establishing coherence between the curriculum and assessment goals.

8.6 Contributions to Research and Practice in Science Education

The FRA and GIS have the potential to contribute to various aspects of research in science education. As tools for conceptual analysis, they can be used to examine research on nature of science or research in science education in general. They can help identify trends in the research literature. For example, GIS can help query to what extent the economical aspects of science have been a research focus in science education. In a similar vein, GIS can help further articulate existing bodies of research. If studies historically fell into one or two categories of the FRA, the GIS provides a chance to reflect on where else the work could go next. For example, work on argumentation in science education typically covered argumentation as a particular instance of scientific practices and scientific knowledge (e.g. Erduran, 2007; Erduran, Simon, & Osborne, 2004). GIS can help identify missing NOS aspects, for example the impact of organizational structures in the validation of scientific arguments and implications for the design of learning environments. As analytical heuristics, they can help identify various trends and emphases as well as missing aspects of NOS in science education research and policy.

The expanded FRA and the GIS articulate and reconcile the tensions between a set of nature of science ideas that are rooted in general principles that cut across the sciences and nature of science ideas that are rooted in specific science domains. What are the GIS? Are they generic or domain-specific? We contend that they are both. They are generic in terms of the broad category, such as scientific practices. However, the category is vacuous without the content-specific details. The teaching content of an FRA category is bound by reflective thinking of a specific domain. This reflective thinking emerges from insights gained from philosophical, historical, social and cultural studies of science. It is useless to talk about generic practices, generic methods without pointing to specific practices and specific methods from which these generic ones were derived. On its own, we can take any FRA category, for example methods and methodological rules, and discuss methodological possibilities, but that is not the point we are trying to make in our treatise of FRA in science education. By the same token, it can be argued that methods are always taught in connection with science. In the absence of a reflective component anchored in a particular science domain, the relevance of the diversity of methods could be easily missed.

To continue with the example of the methods category, the purpose for discussing these methods is to communicate how different fields of study lean on a variety of *specific* methods. Even though emphasis on the various methods differs across science domains (e.g. the role of experimentation in astronomy versus chemistry), noting these differences in the context of progressing through different domains across the science curriculum in a school year or an entire educational career provides opportunities for building a profound understanding of the range of methods scientists use to generate trustworthy findings. Domain-specificity can also contribute to complex theoretical narratives leading to deeper understanding of not only the methods themselves but also the nature of the knowledge that is generated through the deployment of such methods. This is very different from knowing that scientific methods are diverse at a superficial level. Our approach forces understanding the roots of methodological diversity, why is it useful and what it achieves. In this sense, any serious characterization of scientific methods in general cannot escape the domain-specificity of scientific methods. The following quote elegantly addresses a parallel relationship between science domains as parts and the whole of science:

> Parts and wholes evolve in consequence of their relationship, and the relationship itself evolves. These are the properties of things that we call dialectical: that one thing cannot exist without the other, that one acquires its properties from its relation to the other, that the properties of both evolve as a consequence of their interpenetration. (Levins & Lewontin, 1985, p. 3)

A related but different issue concerns the potential of the FRA to facilitate meta-cognitive awareness of the domain-specific aspects of science. While the FRA is based on an approach that approximates similarities between the various branches of science, it also organizes thinking around the kinds of differences that might exist in branches of science. For example, as discussed in Chap. 6, the way in which chemists and physicists understand 'laws' may have some differences. While various branches of science might have laws as part of the scientific knowledge repertoire, the disciplinary variations can be highlighted.

8.7 Conclusions

The GIS and the FRA on which they are based, provide science educators, specifically teachers and researchers, with heuristic tools for situating scientific values, knowledge, methods, practices and social-institutional systems in ways that can potentially motivate students. These tools promote understanding of science as the interplay of a cognitive-epistemic-social-institutional dynamic that is constantly developing and evolving. Like "scientists [who] produce new knowledge in many domains through generating and analyzing the content of images" (Prain & Tytler, 2013, p. 1), as educators we sought to generate images about science for the purpose of opening up conversations on practical pathways for enriching science teaching and learning. Even though a range of examples were presented in each chapter, it is important to envision the totality of these images in use. For instance, it is vital for educators to consider the content they impart, and how the GIS might be infused within a unit of study, across units of study in a school year, and across an entire K-12 education. The images are iconic meta-cognitive tools that can help teachers and learners consider the nature of scientific aims and values, the nature of data, evidence, arguments and models, and the nature of social values as they operate within the scientific community and the larger society. We hope readers will be inspired to use these tools to support teaching and research agenda in K-12 schools and teacher education settings.

The book is broadly related to the science education research literature on NOS. However, within the historical progression of NOS (e.g. Abd-el-Khalick & Lederman, 2000; Khishfe & Abd-el-Khalick, 2002; Lederman, 1992, 2007; Schwartz, Lederman, & Crawford, 2004) research has been limited in providing a holistic and visual account of nature of science. The holistic aspect relates to the coordination of the cognitive, epistemic and social-institutional dimensions of science while the visual aspect refers to the transformation of such dimensions to visual representations that can be effectively used in application to science education. The GIS provide some practical heuristics with which researchers, curriculum reformers and science teachers can articulate the complexity of NOS in science education.

Our articulation of the FRA categories is related to disparate areas of research in science education, such as studies on socio-scientific issues (e.g. Zeidler, Sadler, Simmons, & Howes, 2005), inquiry-based science teaching and learning (e.g. Duschl & Grandy, 2008; Welch, Klopfer, Aikenhead & Robinson, 1981), metacognition (e.g. Zohar & Dori, 2012), argumentation (e.g. Erduran & Jimenez-Aleixandre, 2008), critical thinking (e.g. Bailin, 2002; Zoller, 1999), history and philosophy of science (e.g. Duschl, 1990; Matthews, 1994), and learning progressions (e.g. Duschl, Maeng, & Sezen, 2011). However our reconceptualization of NOS goes beyond the particular research traditions listed here. In articulating perspectives from philosophy of science, we have (a) appealed to a coherent theoretical rationale on NOS proposed by philosophers of science, (b) developed this theoretical framework extensively, and (c) anchored the extended framework in science curriculum, teaching and learning.

In exploring the interplay between philosophy of science and science education, we have been mindful of the curricular, research and policy contexts of science education, thus drawing on some evidence from these accounts as well selecting perspectives that can have utility and appeal in science education. Ultimately, however, our approach is motivated by a belief that the FRA and GIS will empower learners to engage in science and use their understanding effectively to improve the quality of their lives and the well-being of their communities. Our hope is that the perspectives developed in this book will foster discussion and research for the improvement of science teaching and learning for all students.

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