Visualizing the Nature of Science: Beyond Textual Pieces to Holistic Images in Science Education

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Introduction

“Birds do it, bees do it. Even educated fleas do it. Let’s do it, let’s fall in love,” goes the Cole Porter song popularized by Ella Fitzgerald. As science educators, we can extend an analogy to raise a fundamental question about science: physicists do it; chemists do it; even educated biologists do it. But what is this thing called “science”? We can proceed with further related questions: how do we know what this thing of science is? Where do we turn to answer the question of what science is? Previously (Justi and Erduran 2015), we likened science to a great landscape that is to be explored and understood, such as a major city like London. As vast and complicated a city as London is, we can get a glimpse of its various aspects through the giant Ferris wheel, the London Eye. In using the London Eye analogy, we developed an approach that we called a “Model of Science for Science Education” (Fig. 1) that aims to develop understanding of the various facets of science from different perspectives.

For example, one can have a view of science from a historical, a philosophical, a sociological or an economical perspective. Depending on the place of the individual disciplinary “capsule”, the landscape will be understood in various ways. Furthermore, depending on the theoretical orientation and the diversity of orientations from each disciplinary framework, the view will be different from the *Science Eye* (Fig. 2).

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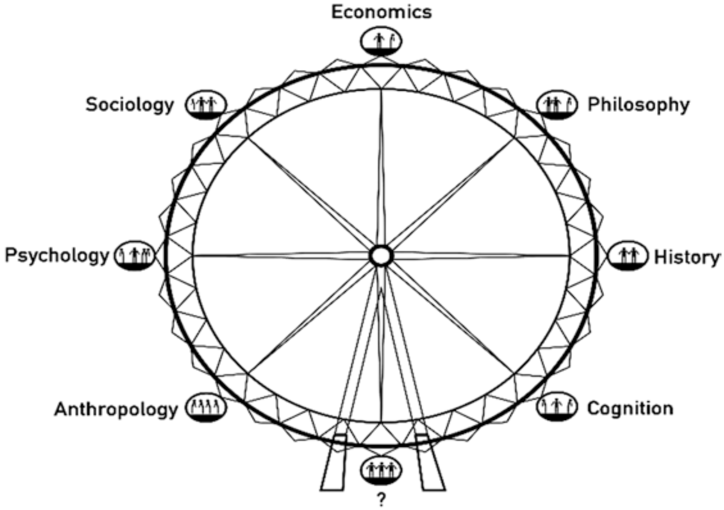

Fig. 1 Model of Science for Science Education (Justi and Erduran 2015)

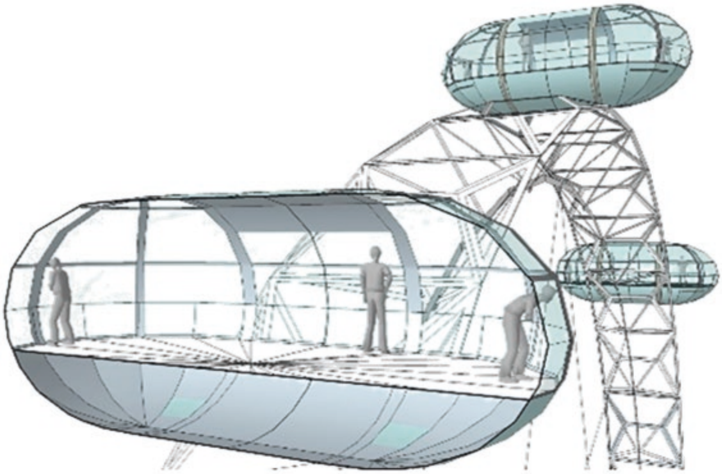

Fig. 2 "Science Eye" and disciplinary variations in understanding science (From Justi and Erduran 2015)

The visual representations in Figs. 1 and 2 capture the disciplinary perspectives that as science educators, we can appeal to in addressing the question "*What is this thing called 'science'?*" We can appeal to the anthropological studies on science to gain understanding of how scientific cultures and norms operate. Understanding of such issues might then provide some insight into how classroom learning cultures of science can be designed to have scientific authenticity. The representations are dynamic in nature communicating the ever-changing accounts of science. They also illustrate a collective and connected account on science, providing an overview of how we get to know what science is about.

As in the case of the preceding analogy, often we have appealed to contemporary philosophy of science in order to understand the nature of science (NOS). NOS is a significant body of work that has been of interest to science educators for at least the 1960s (e.g. Ackerson and Donnelly 2008; Abd-El-Khalick et al. 1998; Allchin 2013; Clough 2007; Duschl and Grandy 2013; Irzik and Nola 2011; 1968; Klopfer 1969; Lederman et al. 2002; Matthews 2014; McComas et al. 1998; Schwartz et al. 2004). NOS has been promoted in science curricula from around the world because it can help in supporting the development of scientific literacy (DfES/QCA 2006; CDC 1998). The contemporary arguments for the inclusion of NOS in science curriculum policy mirror earlier initiatives. For example, a crucial forerunner of science curriculum reform in the USA, Project 2061: *Science For All Americans*, a report prepared by the American Association for the Advancement of Science (1989), had articulated the view that an understanding of the nature of science is one of four categories considered essential for all citizens in a scientifically literate society.

The chapter aims to highlight that research on NOS in science education has primarily focused on textual representations of NOS and has not paid sufficient attention to the visualization of NOS. The "Science Eye" presented earlier is an example that highlights how a complex idea such as how we get to know about NOS can be communicated through visual analogies. Various aspects of NOS (e.g. scientific method, scientific knowledge) can also be represented and communicated visually. The chapter provides an overview of such visual tools that can be adapted for science education.

Nature of Science Research in Science Education

Definitions of the nature of scientific knowledge presented in the science education literature are diverse. The work in the 1960s included seminal pieces by Conant (1961) and Klopfer (1969). According to Klopfer (1969), the processes of scientific inquiry and the developmental nature of knowledge acquisition in science depict the nature of science. Klopfer identifies the understanding of how scientific ideas are developed as one of the three important components of scientific literacy. In this view, students must learn how scientific ideas are formulated, tested and, inevitably, revised, and he/she must learn what motivates scientists to engage in this activity. Kimball (1968) developed a model of the nature of science following an extensive review of literature on the nature and philosophy of science. The main statements guiding his model were the following:

1. The fundamental driving force in science is curiosity concerning the physical universe. It has no connection with outcomes, applications or uses aside from the generation of new knowledge.
2. In the search for knowledge, science is process-oriented; it is a dynamic, ongoing activity rather than a static accumulation of information.

3. In dealing with knowledge as it is developed and manipulated, science aims at ever-increasing comprehensiveness and simplification, emphasizing mathematical language as the most precise and simplest means of stating relationships.
4. There is no one "scientific method" as often described in school science textbooks. Rather, there are as many methods of science as there are practitioners.
5. The methods of science are characterized by a few attributes which are more in the realm of values than techniques. Among these traits of science are dependence upon sense experience, insistence on operational definitions and the evaluation of scientific work in terms of reproducibility and of usefulness in furthering scientific inquiry.
6. A basic characteristic of science is a faith in the susceptibility of the physical universe to human ordering and understanding.
7. Science has a unique attribute of openness, both openness of mind, allowing for willingness to change opinion in the face of evidence, and openness of the realm of investigation, unlimited by such factors as religion, politics or geography.
8. Tentativeness and uncertainty mark all of science. Nothing is ever completely proven in science, and recognition of this fact is a guiding consideration of the discipline (Kimball 1968: 111–112).

Some of the work conducted in the 1970s included that of Showalter (1974) who used the concepts tentative, public, replicable, probabilistic, humanistic, historic, unique, holistic and empirical to characterize the nature of scientific knowledge. After conducting a review of literature on the nature of scientific knowledge, Rubba and Anderson (1978) consolidated the nine concepts identified by Showalter into a six-factor model called "A Model of the Nature of Scientific Knowledge". The six factors included by Rubba and Anderson are defined as amoral (scientific knowledge itself cannot be judged as morally good or bad), creative (scientific knowledge is partially a product of human creativity), developmental (scientific knowledge is tentative), parsimonious (scientific knowledge attempts to achieve simplicity of explanation as opposed to complexity), testable (scientific knowledge is capable of empirical test) and unified (the specialized sciences contribute to an interrelated network of laws, theories and concepts).

Other researchers such as Cotham and Smith (1981) use the terms "tentative" and "revisionary" to describe the nature of scientific theories. The tentative component of this conception highlights the inconclusiveness of all knowledge claims in science. The revisionary component indicates the revision of existing scientific knowledge in response to changing theoretical frameworks. While NOS has been used as terminology in the literature to represent the same facets as scientific knowledge, it is usually presented in a broader context. This broader context includes not only the nature of scientific knowledge but the nature of the scientific enterprise and the nature of scientists as well (Cooley and Klopfer 1963).

More contemporary accounts of NOS in the science education research literature have been reviewed by Chang et al. (2010) who traced the literature between 1990 and 2007. The key proponents during this period in science education (Abd-El-Khalick 2012; Lederman et al. 2002; McComas and Olson 1998) have outlined a set of statements that characterize what has been referred to as a "consensus view" of the nature of science. The key aspects of this approach are as follows:

1. Tentativeness of scientific knowledge: Scientific knowledge is both tentative and durable.
2. Observations and inferences: Science is based on both observations and inferences. Both observations and inferences are guided by scientists' prior knowledge and perspectives of current science.
3. Subjectivity and objectivity in science: Science aims to be objective and precise, but subjectivity in science is unavoidable.
4. Creativity and rationality in science: Scientific knowledge is created from human imagination and logical reasoning. This creation is based on observations and inferences of the natural world.
5. Social and cultural embeddedness in science: Science is part of social and cultural traditions. As a human endeavour, science is influenced by the society and culture in which it is practiced.
6. Scientific theories and laws: Both scientific laws and theories are subject to change. Scientific laws describe generalized relationships, observed or perceived, of natural phenomena under certain conditions.
7. Scientific methods: There is no single universal step-by-step scientific method that all scientists follow. Scientists investigate research questions with prior knowledge, perseverance and creativity (Lederman et al. 2002: 500–502).

The "consensus view" of NOS has led to a major body of empirical studies in science education (Ackerson and Donnelly 2008; Abd-El-Khalick and Lederman 2000). While many science educators agree with the key tenets of this definition of NOS, several points of debate have been prevalent in the community. For example, some authors (e.g. Lederman 2007) have advised that while NOS and scientific inquiry are related, they should be differentiated. The main premise of this argument is that "inquiry" can be specified as the methods and procedures of science, while the NOS concerns more the epistemological features of scientific processes and knowledge.

Grandy and Duschl (2007) have disputed such distinctions on the basis that they "greatly oversimplify the nature of observation and theory and almost entirely ignores the role of models in the conceptual structure of science" (2007: 144). Although Lederman (2007) advocates using the phrase "nature of scientific knowledge" (rather than NOS) to avoid the conflation issue, scientific inquiry (especially "scientific methods") has been considered an important aspect of NOS in other researchers' work (e.g. Ryder et al. 1999). A related set of research studies highlight the epistemological goal of inquiry (e.g. Sandoval 2005) and epistemological enactment through inquiry (e.g. Ford 2008).

The Missing Pieces in NOS Research in Science Education

The literature on NOS in science education has focused our attention on an important aspect of science to promote in science teaching and learning. It has provided an overview of some key ideas and has resulted in considerable empirical research. Yet there are still some questions that remain to be addressed as follows:

- Nature of *which* science is meant by NOS.
  - *How can we account for domain specificity as well as domain generality of science?*
- What's the big picture in terms of how the various components of NOS are related to each other?
  - *How can we move from disconnected fragments that are about declarative statements about NOS to holistic accounts of science in school science that can have some pedagogical utility?*

In order to address the first question about NOS, let's take one often-cited misunderstanding that concerns scientific laws. Classified as the number one NOS myth by McComas and Olson (1998: 54), many individuals tend to believe "...that with increased evidence there is a developmental sequence through which scientific ideas pass on their way to final acceptance as mature laws". Involved in this belief is the thought that science starts out with facts and progresses to hypotheses, then to theories then, when confirmed, to laws. Another myth pertains to the idea that scientific laws are absolute (McComas and Olson 1998). A "law" is typically defined as "a regularity that holds throughout the universe at all places and at all times" (Salmon et al. 1992: 17). Some laws in chemistry like Avogadro's law (i.e. equal volumes of gases under identical temperature and pressure conditions will contain equal numbers of particles) are quantitative in nature, while others are not. For example, laws of stoichiometry are quantitative in nature and count as laws in a strong sense. Others rely more on approximations and are difficult to specify in an algebraic fashion. Scerri (2000) takes the position that some laws of chemistry are fundamentally different from laws in physics. Further contrasts of the nature of domain specificity of laws in chemistry and biology have been examined in the context of science education (Dagher and Erduran 2017).

In addressing the second question, I want to highlight a typical activity that is carried out in science lessons. We referred to classification in school science as a sorting activity or a tool for organizing observations with little or no attention given to its explanatory and predictive power or to how it fits within a broader theoretical framework (Erduran and Dagher 2014a: 71). For instance, students might be asked to classify objects for which there is no broader theoretical significance, such as sorting out buttons and pencils. This sense of classification could be considered as an activity. This is in sharp contrast to how scientists use classification not only to organize existing relationships but also predict new ones all the while operating within a broader theoretical framework. Classification serves an epistemic purpose in explaining phenomena through scientific knowledge in the form of models and theories. Another example from chemistry is how Mendeleev's classification of elements on the basis of periodicity led to the prediction of gallium, hence highlighting the role that classification can play in predictions. Conceiving of classification as practice in science education lifts the level of engagement with it from being an isolated activity to one that is situated in the broader epistemic, cognitive and social-institutional practices of the discipline. Hence, our discussion brings us now to three major questions:

- How can we produce holistic accounts of NOS in school science for meaningful learning?
- How can we account for disciplinary variations as well as similarities in NOS?
- What visual tools can we produce to facilitate the teaching and learning of NOS?

In our work, we have taken an approach to NOS that can account for domain-general as well as domain-specific aspects of science (Erduran and Dagher 2014a). For this purpose, we found the so-called family resemblance approach (FRA) (Irzik and Nola 2014) useful as will be described in the following sections. This approach has also helped us to think about NOS in a unified manner where declarative and disconnected fragments of verbal statements could be unified into meaningful wholes. This is because the FRA is based on a set of categories such as the aims and values, knowledge, practices, methods, social interactions and institutional aspects of science that lead to a coherent narrative about science.

Rationale for the Family Resemblance Approach to NOS

In our rationalization of FRA for science education (Erduran and Dagher 2014a; Dagher and Erduran 2016, 2017), we have appealed to the work of philosophers of science Irzik and Nola (2014). The advantage of using FRA to characterize a scientific field of study is that it allows a set of broad categories to address a diverse set of features that are common to all the sciences and the activities carried out within them. This is particularly useful in science, where all disciplines share common characteristics but not all of these can define science or demarcate it from other disciplines. Irzik and Nola (2014) present the example of observation (i.e. human or artificial through the use of detecting devices) and argue that even though observing is common to all the sciences, the very act of observing is not exclusive to science and therefore does not necessarily allow grant family membership. The same applies to other practices such as inferring and data collection, whereby these are shared by the sciences but their use is not necessarily limited to science disciplines.

The discovery of the structure of DNA can provide an example to illustrate the broad categories that underlie the FRA framework. James Watson and Francis Crick published the double-helix model of DNA in Nature in 1953 (Olby 1994). Their account was based on the X-ray diffraction image generated by Rosalind Franklin and Raymond Gosling a year earlier as well as information from Erwin Chargaff on the pairing of bases in DNA. Maurice Wilkins and his colleagues had also published results based on X-ray patterns of DNA which provided evidence for the double-helix model proposed by Watson and Crick. Watson, Crick and Wilkins were acknowledged jointly for the discovery of the structure of DNA following the death of Franklin. The extent to which Franklin's contribution has been acknowledged has emerged as a contentious issue. In particular, there is widespread recognition that Franklin experienced sexism from Watson, Crick and Wilkins (Sayre 2000/1975) (Table 1).

The DNA example illustrates how the FRA framework can be applied to a scientific topic with implications for science education. Clearly, the argument for the inclusion of these various features of science is not new. Numerous science education researchers have already made this argument. However, what is novel about this approach in relation to NOS literature is that when covered together, in a collective and inclusive manner, NOS is presented to learners in a more authentic and coherent

Table 1 Application of FRA categories to the context of DNA discovery

FRA	DNA example
Aims and values	Although the base, sugar and phosphate unit within the DNA was known prior to the modelling carried out by Watson and Crick, the correct structure of DNA was not known. Their quest in establishing the structure of DNA relied on the use of such existing data objectively and accurately to generate a model for the structure. Hence the values exercised included objectivity and accuracy
Practices	In their 1953 paper in Nature, Watson and Crick provide an illustration of the model of DNA as a drawing. Hence they engaged in providing representations of the model that they built. They also included the original X-ray diffraction image generated by Franklin on which their observations were based. The scientific practices of representation and observation were thus used
Methodology	The methods that Watson and Crick used were Franklin's X-ray diffraction data which relied on non-manipulative observation. Hence, the methodology involved particular techniques such as X-ray crystallography and observations
Knowledge	The main contribution in this episode of science is that a model of the structure of DNA as a double helix was generated. This model became part of scientific knowledge on DNA and contributed to a wide range of scientific disciplines including chemistry, molecular biology and biochemistry
Social and institutional context	This episode illustrates some of the gender and power relations that can exist between scientists. There is widespread acknowledgment in the literature and also by Crick himself, for instance, that Franklin was subjected to sexism and that there was institutional sexism at King's College London where Franklin worked (Sayre 2000/1975, p. 97). The DNA case also illustrates that science is both a cooperative and a competitive enterprise. Without Franklin's X-rays, Watson and Crick would not be able to discover the correct structure of DNA. This is the cooperative aspect. However there was also competition within and across teams of researchers

Erduran and Dagher (2014a: 30)

fashion. When students confront this and other examples positioned in a similar fashion (where now comparative aspects across examples can be pursued as well), the "family resemblance" element can also be drawn in. For instance, the precise nature of observation in terms of it being a "scientific practice" in the DNA example can be contrasted with another instance, say, an example from astronomy to draw out the similarities and differences of observation in different branches of science. The domain-specificity aspects of the FRA approach is illustrated through the examples from different topics from biology, chemistry and physics (Table 2).

Table 2 Articulation of FRA components across science topics in Key Stage 4 in the National Curriculum for England and Wales (2013)

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 classifications 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 the two communities
Methods	Compare the different methods scientists 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

(continued)

Table 2 (continued)

Science topic	Cell biology	Periodic table	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

From Erduran and Dagher (2014a: 172)

Fig. 3 FRA wheel: science as cognitive-epistemic and social-institutional system (Erduran and Dagher 2014a: 28)

We have extended Irzik and Nola's (2014) original set of categories in the FRA framework and added further categories to "social organizations and interactions", "political power structures" and "financial systems". Furthermore, we have transformed their list of categories to a visual representation in the form of a wheel where the categories are projected in an interactive manner (Fig. 3).

The FRA wheel hence provides us with a visual tool that is a summary of some major aspects of NOS. It is holistic and dynamic in that the various categories are conceptualized together, whereby they are related to each other. The FRA wheel is thus a "meta" tool in organizing some key concepts. It is also generative because as

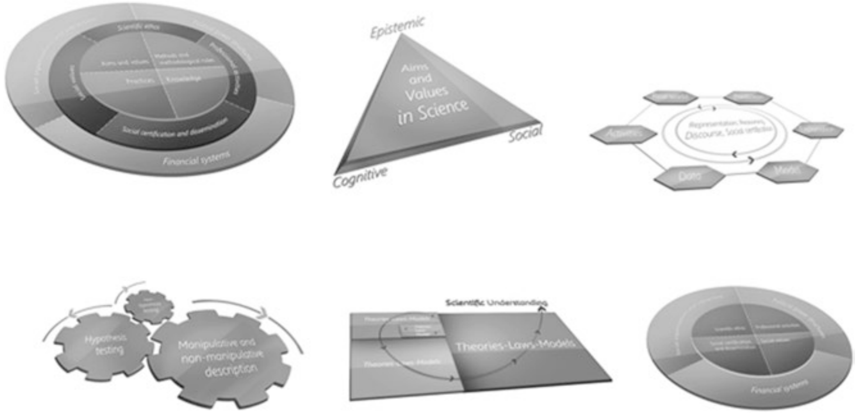

Fig. 4 Generative Images of Science (Erduran and Dagher 2014a: 164)

science educators, we can use it to generate some guidelines for how the various aspects of NOS can be considered for pedagogical, curricular and other educational purposes. Each category has further been articulated with a separate visual tool that helps unpack that particular category. Collectively, we called these visual tools *Generative Images of Science* (GIS) because they help generate educational ideas about NOS (Fig. 4).

Educational Applications of the FRA Framework

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. In many curricula from around the world (e.g. Achieve, Inc., 2013 in the USA), basic understandings about a topic such as heredity are developed across the years along a developmental pathway where a more sophisticated understanding is targeted at secondary schooling. The FRA wheel can help structure curricular thinking and planning so that the various aspects of NOS can be covered in unison and in a consistent fashion across years of schooling (Fig. 5). FRA may increase in sophistication as science concepts get more complex moving from primary to secondary school (Erduran and Dagher 2014a).

The FRA categories can also 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, a term or a sequence of lessons (Fig. 6). 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.

Fig. 5 FRA categories across schooling (Erduran and Dagher 2014a: 167)

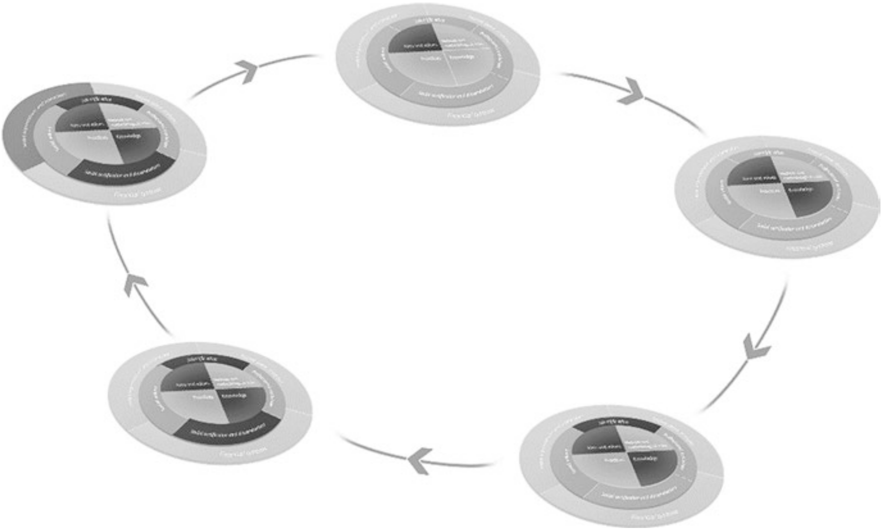

Fig. 6 Rotating emphases on FRA categories (Erduran and Dagher 2014a: 173)

The FRA framework can thus serve as a tool for thinking about what content the science curriculum should have and how it should be structured. In this vein, Kaya and Erduran (2016) have done a recent curriculum analysis study where they have contrasted two Turkish curricula using the FRA framework. The results of this analysis are consistent with previous research (Erduran and Dagher 2014b) in terms of the presence of some categories such as aims and values, knowledge, practices and methods. In order to investigate the potential of FRA for comparative international curriculum analysis, we focused on those categories that were not well represented in our analysis as well as those of other researchers. In the work of those researchers as well as ours, there is limited reference to the categories of professional activities, financial systems and political power structures. Hence we focused on how these categories compare across curriculum documents from three example countries: Turkey, the USA and Ireland.

With respect to the “social organizations and interactions” category, only the Turkish curriculum includes a statement of “The students investigate and present the studies conducted by public/private institutions and civil society organizations that contribute to the development of chemical industry in our country” (MEB 2013: 34). Related to “scientific ethos” category, there is a statement as follows: “Conduct research relevant to a scientific issue, evaluate different sources of information, understanding that a source may lack detail or show bias” (MEB 2013, 17). This example of “scientific ethos” is present only in the Irish curriculum, while the US and Turkish curriculum statements did not include any instances of this category. The lack of reference to the “professional activities” category is consistent with the curriculum analysis study by Erduran and Dagher (2014b) who reported the FRA categories in the Irish science curriculum. The “scientific ethos” category is referred to by only the NCCA in Ireland, while “social organizations and interactions” category is referred to by only MEB in Turkey. Overall, the NGSS in the USA referred to only one, whereas the NCCA in Ireland referred to two and MEB in Turkey referred to three out of the seven categories.

What the preceding discussion illustrates is that the FRA framework can be adapted as an analytical tool to investigate the science curriculum and to carry out international comparative curriculum analysis. This aspect of the work has far broader and more significant implications for science education than just NOS in science education as a research because it concerns the fundamental problem of what is included in the science curriculum in the first place. Similar concerns are raised in the context of the science curricula in Taiwan (Yeh et al. 2017).

Conclusions and Implications

The chapter is broadly related to the science education research literature on NOS. However, within the historical progression of NOS (e.g. Abd-el-Khalick and Lederman 2000; Lederman 1992, 2007; Schwartz et al. 2004), research has been limited in providing a holistic and visual account of NOS. 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. In particular, the GIS (Generative Images of Science) provide some practical heuristics with which researchers, curriculum reformers and science teachers can articulate the complexity of NOS in science education. Initial empirical validation of GIS in science teacher education are encouraging (e.g. Kaya and Erduran 2016; Saribas and Ceyhan 2015).

Recent curriculum analysis studies (Kaya and Erduran 2016; Erduran and Dagher 2014b; Yeh et al. 2017) point out that FRA (family resemblance approach) categories about the epistemic and cognitive context such as aims and values, scientific practices and scientific knowledge were included in curriculum documents. However, the inclusion of FRA categories related to social-institutional context was limited in the curricula of various curriculum documents. Even in the case of those positive instances of FRA categories being present in the curriculum documents, there seems to be a trend in presenting these categories in a rather fragmented set of statements that do not add to a coherent overall vision for that category. For example, regarding scientific knowledge, model as a type of scientific knowledge is mentioned in the curriculum, but the relationship and coherence among theories, laws and models as types of scientific knowledge were not addressed in the curricula (Kaya and Erduran 2016). FRA is a framework for articulating NOS in a comprehensive manner such that gaps and missing links within the science curriculum can be identified and addressed. We have illustrated that representations like the "Science Eye" (Justi and Erduran 2015) and GIS (Erduran and Dagher 2014a) can provide some visual tools to conceptualize and communicate aspects of NOS. Without a comprehensive, holistic and inclusive approach to the content of the science curriculum, it is dubious how we as science educators can address the fundamental question of science education: *What is this thing called "science"?*

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