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ARTICLE

Reconceptualizing the Nature of Science for Science Education

Why Does it Matter?

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Abstract Two fundamental questions about science are relevant for science educators: (a) What is the nature of science? and (b) what aspects of nature of science should be taught and learned? They are fundamental because they pertain to how science gets to be framed as a school subject and determines what aspects of it are worthy of inclusion in school science. This conceptual article re-examines extant notions of nature of science and proposes an expanded version of the Family Resemblance Approach (FRA), originally developed by Irzik and Nola (International handbook of research in history, philosophy and science teaching. Springer, Dordrecht, pp 999–1021, 2014) in which they view science as a cognitive-epistemic and as an institutional-social system. The conceptual basis of the expanded FRA is described and justified in this article based on a detailed account published elsewhere (Erduran and Dagher in Reconceptualizing the nature of science for science education: scientific knowledge, practices and other family categories. Springer, Dordrecht, 2014a). The expanded FRA provides a useful framework for organizing science curriculum and instruction and gives rise to generative visual tools that support the implementation of a richer understanding of and about science. The practical implications for this approach have been incorporated into analysis of curriculum policy documents, curriculum implementation resources, textbook analysis and teacher education settings.

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The ideas in this paper are consolidated from a detailed account of the expanded FRA described in Erduran and Dagher (2014a).

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1 Introduction

The nature of science (NOS) has been a predominant area of research in science education in the past few decades as evidenced by the proliferation of published works in this domain (Abd-El-Khalick, Bell, & Lederman, 1998; Alters, 1997; Driver, Leach, Millar, & Scott, 1996; Eflin, Glennan, & Reisch, 1999; Lederman, 1992; McComas, Clough, & Almazroa, 1998; Rubba & Anderson, 1978; Smith, Lederman, Bell, McComas, & Clough, 1997). Believed in part to be a critical component of scientific literacy as early as the 1960s, attention to supporting an understanding of science from philosophical and historical perspectives gained momentum in the USA, especially in the last two and half decades with the publication of curriculum policy documents, Science for all Americans (AAAS, 1989) and the Science Education Content Standards (NRC, 1996). Addressing the nature and history of science thus became an important science education content standard that was expected to support content standards in the physical, earth and life sciences, alongside a focus on inquiry and technological design.

The focus on nature of science in science curriculum standards in the last two decades is not unique to the USA. A comparative study of eight curriculum standards that included four from the USA and four from Australia, Canada, England/Wales and New Zealand reveals a similar international trend (McComas & Olson, 1998). Recent policy documents in other parts of the world show a similar tendency for including nature of science in varying levels of detail as in the case of Ireland (Erduran & Dagher, 2014b).

Chang, Chang, & Tseng's (2010) review of the literature between 1990 and 2007 notes emphasis on a set of statements that has been referred to as a "consensus view" of the nature of science (Abd-El-Khalick, 2012; Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002). This view supports emphasis on seven key aspects or tenets deemed appropriate for school science that include: (1) Tentativeness of Scientific Knowledge, (2) Observations and Inferences, (3) Subjectivity and Objectivity in Science, (4) Creativity and Rationality, (5) Social and Cultural Embeddedness in Science, (6) Scientific Theories and Laws and (7) Scientific Methods.

The "consensus view" has led to a major body of empirical studies on student and teacher conceptions of NOS in science education (Ackerson & Donnelly, 2008; Abd-El-Khalick & Lederman, 2000) and has culminated in several points of debate in the science education community. One of the issues in this debate for instance pertains to Lederman's (2007) stance that even though 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 (2008) have disputed these arguments on the basis that they "greatly oversimplify the nature of observation and theory and almost entirely ignore the role of models in the conceptual structure of science" (p. 144).

On another level, Duschl and Grandy (2011) lament that the contemporary accounts of NOS in science education have not sufficiently addressed the dialectical processes that shape the role of theory, evidence, explanation and models that are involved in the development of scientific knowledge. They believe that targeting understanding of the revision and modification of methods of inquiry as well as knowledge evaluation in science as learning outcomes for understanding the nature of science is a neglected area:

> One of the important findings from the science studies literature is that not only does scientific knowledge change over time, but so, too do the methods of inquiry and the criteria for the evaluation of knowledge change. (Duschl & Grandy, 2011, p. 17)

In other words, the focus in the consensus view, for instance, on the tentative nature of scientific knowledge does not motivate consideration of change in scientific methods and criteria that underlie shifts in this knowledge base.

Additional critiques focus on the declarative statements characteristic of the consensus view, which may constrain thought about NOS. Clough (2007) has suggested turning the NOS tenets from declarative statements into questions that promote discussion, rather than presenting them as forgone conclusions about what science is. Expressing different but related set of concerns, Yacoubian (2012) notes that the consensus view does not provide guidance for applying NOS ideas to various ends, distorts the substantive content of NOS and does not offer a developmental trajectory for teaching NOS content. His resolution supports teaching an inquiring stance toward nature of science, a point similar to the one made by Clough. He offers, however, an elaborate critical thinking CT-NOS framework to create developmentally appropriate NOS enriched lessons.

Suggesting a drastic departure from the consensus view, Allchin (2011) calls for "re-framing current NOS characterizations from selective lists of tenets to the multiple dimensions shaping reliability in scientific practice, from the experimental to the social, namely to Whole Science" (p. 518). He argues that many items related to science as an enterprise, for instance, the role of funding, motivations, peer review, cognitive biases, fraud and the validation of new methods, are absent in the "consensus view" NOS list, and yet they are "*unified by the theme of reliability*." From Allchin's perspective, this shift better prepares students for dealing with how claims might fail and how scientists deal with sources of error (Allchin, 2011, p. 524). Allchin believes that NOS in science education needs to be reframed to be sensitive to all dimensions of reliability in scientific practice. He states that:

> Whole Science, like whole food, does not exclude essential ingredients. It supports healthier understanding. Metaphorically, educators must discourage a diet of highly processed, refined "school science." Short lists of NOS features should be recognized as inherently incomplete and insufficient for functional scientific literacy (Allchin, 2011, p. 524).

Noting the limitations of the consensus view, Matthews (2012) suggests replacing the notion of "nature" of science (NOS) with "features" of science (FOS) that encompass a more inclusive range of ideas about science than would be possible by strictly following an epistemological emphasis, or focusing on scientific knowledge, as is the case with the "consensus view." The FOS features that Matthews has proposed resemble a disparate set of ideas some of which reflect epistemic aspects of science on the one hand (e.g., explanation, theory choice and rationality), while others reflect a philosophical stance (e.g., feminism, realism and constructivism). In this sense, these features of science address different levels of organization of science and philosophy of science. The myriad features that Matthews proposes are not well justified and do not provide a coherent vantage point as does Allchin's with his focus on the reliability theme, or Yacoubian's with his focus on the critical thinking theme. Furthermore, it is unclear how philosophical positions as feminism and realism can be made relevant to the context of the proposed FOS-oriented school science.

The question of "*who decides for science education organizations and researchers the primarily philosophically based question of what are the tenets of the NOS?*" raised by Alters (1997, p. 42) two decades ago, remains pertinent to current discussions. Alters concluded from his empirical study on the perceptions and recommendations of philosophers of science that they should be brought into the picture not only to examine the different proposals about the NOS beliefs, but also to provide some guidance in establishing more precise criteria for the NOS. In an effort to invite multiple perspectives to weigh in on these issues, Osborne and colleagues' (2003) surveyed a sample of 23 experts from diverse backgrounds that included science educators; scientists; historians, philosophers and sociologists of science; experts engaged in work to improve the public understanding of science; and expert science teachers. Their study revealed few themes on which the experts seemed to have some level of consensus. Five themes were subsumed under methods of science, two fell under the nature of scientific knowledge, and one fell under institutions and social practices of science. The authors concluded that "no one method and no one group of individuals can provide a universal solution as to what should be the essential elements of a contemporary science curriculum" (Osborne et al., 2003, p. 715).

It is clear from this brief overview that while questions on what nature of science content is optimal for school science have been settled for proponents of the consensus view through responses to critics (Smith et al., 1997; Schwartz, Lederman, & Abd-El-Khalick, 2012), they are far from settled for others who have voiced grave concerns about its limitations. In this paper, we describe a Family Resemblance Approach (FRA) to nature of science, proposed by philosophers of science Irzik and Nola (2014). After describing their approach, we elaborate on and expand their FRA notion into a useful framework for developing a more comprehensive understanding of the nature of science with clear implications for curriculum and instruction.

2 Theoretical Framework

The Family Resemblance Approach (FRA) to the nature of science offers a fresh way of pointing out those overlapping features of science disciplines without overly generalizing them to all other sciences. It points to a wide range of shared and distinctive scientific practices, methodologies, aims and values, social norms and the very aspects that contextualize and frame scientific knowledge. To exclude any of these is to deny access to key aspects of these disciplinary elements and consequently results in limited attention to factors that influence the formation and validation of scientific claims.

What is the Family Resemblance Approach to NOS? Basing their notion of family resemblance on a modified version of Wittgenstein's original work, Irzik and Nola (2014) describe the Family Resemblance Approach to nature of science as follows:

> Consider a set of four characteristics {A, B, C, D}. Then one could imagine four individual items which share any three of these characteristics taken together such as (A&B&C) or (B&C&D) or (A&B&D) or (A&C&D); that is, the various family resemblances are represented as four disjuncts of conjunctions of any three properties chosen from the original set of characteristics. This example of a polythetic model of family resemblances can be generalised as follows. Take any set S of n characteristics; then any individual is a member of the family if and only if it has all of the n characteristics of S, or any (n − 1) conjunction of characteristics of S, or any (n − 2) conjunction of characteristics of S, or any (n-3) conjunction of characteristics of S and so on. How large n may be and how small (n − x) may be is something that can be left open as befits the idea of a family resemblance which does not wish to impose arbitrary limits and leaves this to a 'case by case' investigation…. we will employ this polythetic version of family resemblance (in a slightly modified form) in developing our conception of science. (Irzik & Nola, 2014, p. 1011).

Consider that there are characteristics common to all sciences and some that are rather specific in emphases to particular sciences (Dagher & Erduran, 2014; Erduran, 2007). For example, many science disciplines share such practices as collecting data and making inferences. Other features of activities of science such as experimentation, however, might be differentiated. Irzik and Nola (2014) give the example of astronomy and earth sciences.

These domains cannot possibly rely on experiments as neither celestial bodies nor earthquakes can be manipulated in the experimental sense. The authors situate the Family Resemblance Approach further by providing a disciplinary approach:

> Let us represent data collection, inference making, experimentation, prediction, hypothetico-deductive testing and blinded randomised trials as D, I, E, P, H and T, respectively. Then we can summarise the situation for the disciplines we have considered as follows:
> Astronomy = {D, I, P, H}; Particle physics = {D, I, E, P, H}; Earthquake science = {D, I, P′, H}; Medicine = {D, I, P″, E, T}, where P′ and P″ indicate differences in predictive power as indicated.
>
> Thus, none of the four disciplines has all the six characteristics, though they share a number of them in common. With respect to other characteristics, they partially overlap, like the members of closely related extended family. In short, taken altogether, they form a family resemblance. (Irzik & Nola, 2014, p. 1013)

The advantage of using the 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 sub-disciplines share a number of common characteristics, but no one specific characteristic per se can be used to define a domain as scientific or to demarcate it from other disciplines. For instance, if we take 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 grant family membership in and of itself. The same applies to other practices such as making inferences and collecting data, whereby these are shared by the sciences, but their use is not necessarily limited to science disciplines.

As biologically related family members share similar features without looking exactly the same, what might be those characteristics we would want to look for to detect family resemblance across science disciplines? Irzik and Nola (2014) describe science primarily as a cognitive-epistemic and social-institutional system. Within the cognitive-epistemic system, they discuss four categories that include: processes of inquiry, aims and values, scientific methodology and methodological rules, and scientific knowledge. Within the social-institutional system, they discuss four categories that include professional activities, scientific ethos, social certification and dissemination of scientific knowledge, and social values of science.

In summary, the FRA provides an account where the domain-general and domain-specific aspects of science can be articulated in relation to one another. From a pedagogical point of view, using the FRA to discuss nature of science escapes an essentialist description of science, for example, as an experimental field of study because that would result in excluding some legitimate science domains such as astronomy, geology or evolutionary biology. The FRA acknowledges both shared and unique features that make various domains scientific.

3 Justifying the Family Resemblance Approach

Unlike the consensus framework that has remained immune to the various critiques, the FRA framework: (1) acknowledges two concerns raised by Duschl and Grandy (2011) about the consensus view: namely that the natures of scientific practices and scientific knowledge should be part of a broader conception of NOS and that such broader conception appeals to models of growth of knowledge and practices (via FRA categories of scientific knowledge and scientific practices); (2) satisfies Matthews' (2012) call to break away from declarative statements to thinking about broader concepts, but proposes different categories for thinking about these features (via FRA representation of science as a cognitive-epistemic and social-institutional system); (3) addresses Allchin's concerns about inadequate inclusion of scientific aims and values and the broader social context (via FRA categories of social-institutional aspects such as social ethos and certification); (4) differs from Clough's view on keeping the consensus view's tenets and turning them into questions, but agrees that NOS content ought to be questioned; and (5) is compatible with Yacoubian's CT-NOS (2011) approach that is strong on the critical thinking component, an important orientation for implementing the FRA approach instructionally. In sum, the expanded FRA approach parts ways with the consensus approach in terms of NOS content while addressing directly the critiques of the consensus view (i.e., Duschl & Grandy, Matthews, Allchin) by reframing the content of NOS. However, the FRA approach leaves room for incorporating instructional approaches like questioning (i.e., Clough) and critical thinking (i.e., Yacoubian) that can facilitate the teaching and learning of NOS.

One of the appealing aspects of the FRA is its ability to consolidate the epistemic, cognitive and social aspects of science in a wholesome, flexible, descriptive but nonprescriptive way. FRA provides focus zones that support the discussion of critical elements about science that can potentially be fruitful for science educators as well as for teachers and students. It creates opportunities for dialog about science from numerous perspectives. It is this invitation to dialog that has intrigued us and provided us a foundational place to develop and expand what Irzik and Nola (2011a, b, 2014) originally argued. As philosophers, they have presented a compelling justification for their framework. As science educators, we recognize in their approach a coherent organizational scheme for addressing different facets of NOS. This has led us to unpack the specific components in this scheme, expand it to include additional categories judged worthy of inclusion, and contemplate the implications of these ideas about science for science education.

There is a marked difference in orientation afforded by the FRA in comparison with the consensus approach to teaching NOS. The FRA addresses a higher level of organization. It involves a *class of concepts* approximating characteristics and involving deep understandings pertaining to each of the following categories: scientific aims and values, scientific knowledge, scientific practices, scientific methods, methodological rules, professional activities, scientific ethos, social certification and dissemination, and social values. In contrast, the consensus view addresses *individual ideas* (comprising the list of declarative statements/tenets listed earlier) that are specific to the nature of scientific knowledge (NOSK) as clarified by Lederman (2007). Because of their level of specificity, they are highly prescriptive and narrow in scope about what students ought to know. In contrast, the FRA approach envisions scientific knowledge, as one of the eight categories in which all the tenets can be subsumed in principle. But the expanded FRA's articulation of the nature of scientific knowledge is not concerned with the consolidation of declarative statements, because it deals with foundational matters pertaining to the role of theories, laws and models in explaining and predicting phenomena and eventually contributing to the growth of knowledge. It addresses how the different forms of knowledge are related to one another and how distinguishing between different levels of theories, for example, allows for a more sophisticated understanding of knowledge claims within and across domains. These types of understandings cannot be captured meaningfully in summary statements.

From the basic and expanded FRA perspectives, students ought to know many more ideas about scientific knowledge than few stated ideas. In this regard, the expanded FRA provides examples of a range of ideas about scientific knowledge that are appropriate for K-12 science education, and allows choice for selecting NOS content that is most relevant to the science content under study. It allows more degrees of freedom in focusing on a bunch of ideas within any set category. This is a fundamental difference between these two approaches. In our view, the higher level of organization in the expanded FRA is precisely its strength as it lends itself to flexible selection, exploration and comparison of those aspects about science that are most relevant to the target science content. Ultimately, the purpose of the FRA as applied in educational settings is neither to teach students individual ideas, nor to teach them specific philosophical doctrines, but rather to promote holistic and contextualized understanding of science.

The FRA captures a metalevel characterization of the key categories related to science in a broad sense. In other words, the FRA is more inclusive of various aspects in its depiction of science. It is the holistic, inclusive, diverse and comprehensive and metalevel conceptualization of FRA that has been appealing to us as science educators. Having awareness of a wider range of NOS issues does not necessarily mean that the curriculum, the teachers and the students will now be burdened with having to cover them. It only invites selecting those issues about science that are of immediate relevance to the big ideas under study. The FRA framework alerts us to the missing components about science in science education such that we could make strategic decisions about which aspect to prioritize when and for what purpose. Furthermore, having a more diverse representation of science has potentially more appeal to wider range of students. For example, students who may not necessarily be drawn to the epistemic dimensions of science may find more motivation and interest in the social-institutional aspects of science. We base this claim on research into STS teaching (Aikenhead, 1994) and student motivation in science (Shumow & Schmidt, 2014), as well as considerations associated with teaching science from a humanistic perspective (Aikenhead, 2007). Obviously, the enactment of the FRA approach in science teaching and learning will provide further insight on this matter. Unarguably, some of the categories represented in the FRA may not conventionally be familiar to science teachers. We envisage this conversation to be the beginning of a new territory of professional development, as well as of research in science education.

Apart from a comprehensive set of categories about the cognitive-epistemic and social-institutional aspects of science, “family resemblance” is a key theme underlying their individual categories. This theme enables the articulation of science through a set of comparisons between the different branches of science, thus approximating a domain-general as well as a domain-specific set of characteristics of science. The “family resemblance” theme provides much needed coherence to how we can envisage science from a more holistic perspective. In other words, while individual components from the particular eight categories might have been captured in other depictions of nature of science, these individual components can remain rather disconnected. The consequence of such lack of coherence between the different categories of science can potentially lead to a limited understanding about science. Often in school science, it is indeed observed that students are introduced to rather discrete set of features of the nature of science without a metalevel and cohesive characterization. The “family resemblance” approach in Irzik and Nola’s account has the potential to inform and generate more pedagogically, cognitively and epistemically sound models for science education.

4 Expanding the Categories of the Family Resemblance Approach

In this section, we discuss a modified/expanded FRA calling attention to ways in which we have intentionally modified or extended some of its components to support educational goals. A full account of the expanded FRA is described in Erduran and Dagher (2014a). Irzik and Nola (2011a, b) initially used the term "activities" to refer to ideas involving processes used in scientific inquiry. In later work (Irzik & Nola, 2014), they referred to them as "scientific processes." The terms "activities" and "processes" are substituted with "practices." Using "scientific practices" in the context of the FRA establishes a healthy distance from the over-use and narrow meanings often associated with scientific process skills in science education, and the generally all-encompassing sense implied by scientific activities. More importantly, it aligns the range of activities involved in this category with those included in the contemporary science education literature (Duschl, Schweingruber, & Shouse, 2007; NRC, 2012).

The original FRA framework (Irzik & Nola, 2011a) included four main categories focused on epistemic aspects of science. In a revised account, Irzik and Nola (2011b) introduced institutional and social norms as a fifth component that encompassed Merton's norms, social values and research ethics. In a more recent account, the authors (Irzik & Nola, 2014) elaborated on the fifth component by transforming it into a social-institutional dimension that includes four clearly defined categories: professional activities, scientific ethos, social certification and dissemination, and social values.

We added three categories that we deem significant for the science curriculum: "social organizations and interactions," "political power structures" and "financial systems" because they impact how science is done and they address aspects of scientific work as it is influenced by societal and cultural forces as noted in the field of science studies. Social organizations and interactions have been described in Knorr-Cetina's (1999) analysis of the professional and employment status of CERN researchers, along with analysis of connections of the scientific enterprise to ties in the military and industry by Kaiser (2002) and Kleinman (1998). Political power structures address power relations at the level of gendered ideologies (Fox Keller, 1996; Harding & Hintikka, 2003; Pinnick, 2005) and colonial science (Bleichmar, 2012; McLeod, 2000; Schiebinger, 2005). The financial systems category addresses ways in which states and governments shape scientific research priorities as well as the relationship between science and technology from an economics of science perspective (Diamond, 2008; Irzik, 2013; Polanyi, 2002/1969; Radder, 2010).

Furthermore, we believe that student knowledge of these factors will improve their understanding of science in relation to society—a worthwhile goal that is consistent with improving scientific literacy and educating students for citizenship. This is because the reworked framework provides a fair representation of different aspects that might characterize the scientific enterprise. Weaving a broader set of social-institutional aspects into the cognitive-epistemic aspects of science is likely to engage a wider range of learners, especially those who may not be drawn to the cognitive-epistemic aspects. The framework serves the goal of promoting a more balanced and comprehensive account of NOS for all science learners.

How do the components of science as a cognitive-epistemic system relate to those of science as a social-institutional system? This relationship is considered in terms of the FRA Wheel presented in Fig. 1, which includes a set of categories that we have added to the Irzik and Nola (2014) version. The idea can be characterized in the following way. Science as a cognitive-epistemic system occupies a space divided into four quadrants that accommodate its four categories. This circle floats within a larger concentric one also

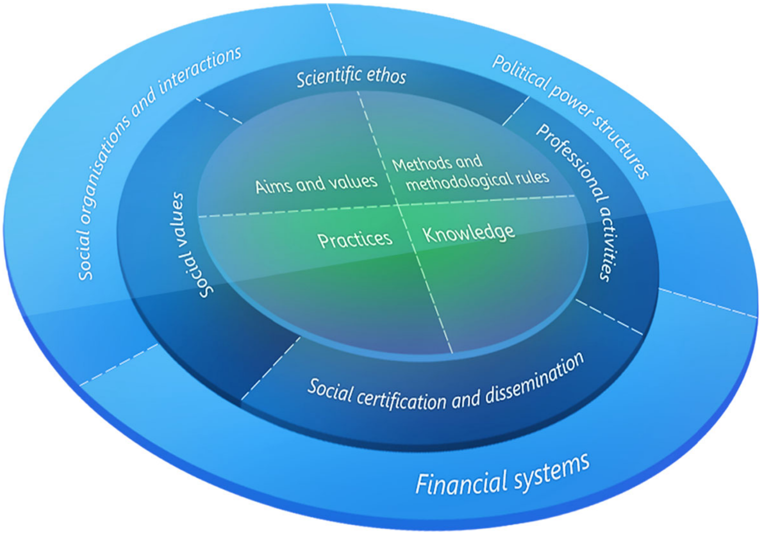

Fig. 1 FRA Wheel: representing science as a cognitive-epistemic and social-institutional system (reprinted from Erduran & Dagher, 2014a, p. 28)

divided into four quadrants, pertaining to the four components of science as a social-institutional system. This, in turn, is surrounded by an outermost circle that includes the three additional components. Locating the three new categories in the outer circle simply reflects the role of societal influences on the scientific enterprise further reinforcing that science is not insulated from the larger society in which it exists. The boundaries between the circles and the individual compartments of the FRA Wheel are porous, allowing fluid movement among its components. In reality, these components are not compartmentalized but flow naturally in all directions.

The FRA Wheel captures an image of science as a holistic, dynamic and comprehensive system with various influences. Components of the epistemic and social systems interact with one another, enhancing or influencing scientific activity. This visual representation that shows how the cognitive, epistemic and social-institutional components of science coexist, provides a departure from representing science as discrete set of facts about science. In other words, it offers a distinctive contribution to NOS research which has not provided such an interactive, visual and holistic account all at the same time. In the course of expanding the FRA, we have developed five additional generative images of science that help explicate the various categories (subsumed under the FRA framework). Because the significance of visualization for facilitating teaching and learning of science is well established (e.g., Gilbert, 2005), we anticipate that the images developed to capture the expanded FRA categories will motivate the exploration of NOS-focused metacognitive questions by teachers and students.

Having reviewed the key features of the FRA framework, our adaptation and expansion of it, the following example illustrates how categories in the FRA Wheel can be used to identify and organize the cognitive-epistemic and social-institutional dimensions that are pertinent to a specific science content such as the discovery of the structure of DNA. 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 on 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 recognition that Franklin experienced sexism from Watson, Crick and Wilkins (Sayre, 2000/1975).

The DNA example illustrates how the FRA framework can be applied in science with implications for science education. Clearly the argument for the inclusion of these various features of science is not new. However, what is novel about using the FRA Wheel to address these different features in relation to one another in a collective and inclusive manner is that a more coherent and authentic picture of science *and* nature of science emerges to students. 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 Irzik and Nola (2014) version of the FRA includes eight categories, and our extension involves eleven. This does not translate into a replacement of a NOS "consensus view" that practically relies on a set of seven tenets, for instance, with a set of 11 FRA categories. The application of FRA is more nuanced in the following ways. First, the adaptation of the FRA for science education is based on contemporary philosophy of science (e.g., Brandon, 1996; Fox Keller, 1996; Mahner & Bunge, 1997; Pickering, 1992; Radder, 2010; Scerri, 2000). Second, the transformation of FRA principles to science education is informed by science education research and practice. Third, the expanded FRA provides an overarching set of principles from which objectives can be constructed or adapted to different core ideas and grade levels. The expanded FRA provides a "systems" approach to organizing science curriculum and instruction that entails systematic consideration of how knowledge about the cognitive-epistemic and social-institutional categories of the FRA relates to the scientific concepts, and ensuring that relevant connections are made between them. It aims to ensure that understanding the nature of science is holistic and comprehensive revolving around key spheres of epistemic and social practices that are grounded in relevant contexts.

5 The Relationship of FRA to Research Traditions and Curriculum Policy Documents

It is worthwhile at this stage to discuss how FRA relates to existing research traditions within science education as well as to curriculum policy. The intention is to be illustrative in order to provide a rationale for the relevance of FRA in science education research and policy. The holistic and inclusive nature of the expanded FRA framework opens up opportunities to incorporate, for instance, history of science (e.g. Allchin, 2013), as well as cognitive models for scientific reasoning, into the design and evaluation of curriculum units. The FRA is also compatible with policy frameworks such as past (AAAS, 1989; NRC, 1996) and recent science education reforms in the USA (NRC, 2012). Even though the *Framework for K-12 Science Education* [*FKSE*] (NRC, 2012) does not designate a specific chapter to discuss the nature of science as the *Science for All Americans* [*SFAA*] document did, the spirit of NOS is integrated throughout its content. The *FKSE* calls for three-dimensional learning focused on: scientific and engineering practices, core ideas and crosscutting concepts.

These dimensions are expected to be taught in an interrelated and coherent way leading to the realization of a normative goal in which “students should develop an understanding of the enterprise of science as a whole—the wondering, investigating, questioning, data collecting and analyzing” (NGSS Lead States, 2013, p. 1). This metalevel of understanding aligns well with the categories of the FRA. In Table 1, we list a few examples of how

Table 1 Application of select FRA categories to the context of DNA discovery (adapted from Erduran & Dagher, 2014a, p. 30)

FRA	DNA example
Aims and values	Although the base, sugar and phosphate unit within the DNA was known prior to the modeling 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.
Methods and methodological rules	The methods that Watson and Crick used Franklin’s X-ray diffraction data which relied on nonmanipulative 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.
Scientific ethos	While some scientific ethos were followed, some ethical standards were violated, especially in relation to “respect for intellectual property” and “respect for colleagues” in relation to the use of one of Franklin’s crystallographic images of DNA.
Social certification and dissemination	Watson and Crick published many papers and so did Franklin. It is reported that Franklin was very close to uncovering the DNA structure, but that Watson and Crick beat her to the publication after they saw one of her x-ray images. Watson and Crick’s paper, as well as a supporting article by Franklin, appeared in the same issue of *Nature*.
Political power structures	This episode illustrates some of the gender and power relations that can exist between scientists. In this case, the focus is mostly on gender issues. 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).
Social organizations and interactions	Crick and Watson worked at the Cavendish Labs on solving the DNA structure, while Franklin and Wilkins worked at the Crystallography Unit at King’s College. Rosalind Franklin and Maurice Wilkins were peers who led separate research groups, but Wilkins initially thought that she was his assistant. Watson attended Franklin’s lecture at King’s College but did not pay attention to it. Wilkins showed Watson & Crick one of Franklin’s x-ray images that provided them with evidence for their theoretical model. The episode illustrates the cooperative and competitive aspects of science.

categories of the FRA correspond to the vision promoted in the *Framework for K-12 Science Education* (2012) and to expectations about students' understanding of the nature of science based on Appendix H in the *Next Generation Science Standards* (NGSS Lead States, 2013). These examples are not the only ones that can be found in the two documents, but they represent well the ideas contained therein. While it was possible to map most of the epistemic statements found in the documents to the core cognitive-epistemic aspects of the expanded FRA, the fewer statements identified along the social-institutional dimension do not spread out across the 7 categories identified by the expanded FRA (Table 2).

Although there seems to be some overlap of the FRA categories with existing statements in policy recommendations, the ways in which US policy documents articulate (or fail to articulate) many elements of the FRA become apparent. For instance, take the reference to the social and institutional dimension. The quoted statements are rather broad and do not necessarily indicate which aspects of the social or the institutional dimensions of science are being emphasized. Because they are too broad, it was not possible to align

Table 2 Alignment of FRA categories with recent reform documents in the USA (reprinted from Erduran & Dagher, 2014a, p. 33)

FRA	*Framework for K-12 Science Education* (NRC, 2012)	*Next Generation Science Standards* (NGSS Lead States, 2013)
Aims and values	"Epistemic knowledge is knowledge of the constructs and values that are intrinsic to science." (p. 79)	"Science Addresses Questions About the Natural and Material World." "Scientific information is based on empirical evidence" (p. 4)
Practices	"…important practices, such as modeling, developing explanations, and engaging in critique and evaluation (argumentation)…" Engaging in argumentation from evidence understanding of the reasons and empirical evidence for that explanation, demonstrating the idea that science is a body of knowledge rooted in evidence (p. 44)	"Students must have the opportunity to stand back and reflect on how the practices contribute to the accumulation of scientific knowledge…. Through this kind of reflection they can come to understand the importance of each practice and develop a nuanced appreciation of the nature of science" (p. 7)
Methodology	"Practicing scientists employ a broad spectrum of methods…" (p. 44)	"Scientific Investigations Use a Variety of Methods" (p. 4)
Knowledge	"Students need to understand what is meant, for example, by an observation, a hypothesis, a model, a theory, or a claim and be able to distinguish among them" (p. 79)	"Science is a Way of Knowing." "Scientific Knowledge is Open to Revision in Light of New Evidence." "Scientific Models, Laws, Mechanisms, and Theories Explain Natural Phenomena" (p. 4)
Social and institutional dimension	"Seeing science as a set of practices shows that theory development, reasoning, and testing are components of a larger ensemble of activities that includes networks of participants and institutions…." (p. 43)	"Science is a Human Endeavor" (p. 4)

them neatly into the seven expanded FRA's social-institutional categories. In many ways, this demonstrates our concern that ideas about science along the social-institutional dimension are addressed in ways that are too general to support meaningful enactment. So while all the categories under the cognitive-epistemic dimension of science are clearly featured, those under the social-institutional dimension are vaguely represented. A similar trend can be seen when the expanded FRA categories are used to evaluate the curriculum policy draft documents in Ireland (Erduran & Dagher, 2014b). Even if the stated curriculum policy goals for NOS make their way into the curriculum, students are likely to gain a partial and decontextualized view of science. Overall, the use of FRA in analyzing the content of the example US and Irish curriculum standards illustrates its educational relevance and its utility in questioning curriculum policy documents and identifying where more emphasis is needed for subsequently enhancing the quality of the science curriculum.

6 Potential Challenges in Applying the FRA in Science Education

The FRA categories may seem complex and confusing at first. We argue, however, that the apparent complexity of the FRA is precisely its core strength. It is complex at first sight, yet it is simple in terms of helping organize thinking about a large number of pedagogically appropriate NOS concepts in terms of few interrelated categories. Because it is suggestive rather than prescriptive at the level of specifying curriculum intent and instructional action, the FRA offers educators a wide range of choices regarding how to embed some of these ideas from each of the five categories in their teaching. In other words, this range of choices is advantageous because it does not mandate a specific set of ideas to be taught in relation to a given content, but invites the selection of relevant ideas along each category as they relate to the content. Educators seeking a short list of NOS statements to incorporate into classroom instruction will find instead guiding principles that need to be unpacked and embedded within the content they are teaching. These guiding principles are not declarative statements. They are contextual domains (cognitive, epistemic, social and institutional) that can be explored and translated into practical teaching and learning outcomes.

The FRA categories include some familiar themes in the science education literature, such as scientific practices, scientific methods, and social certification and dissemination; and other less familiar ones such as aims and values, scientific ethos, social organizations and interactions. The three new categories we introduced may seem either marginal or controversial to bring to students' attention. For example, the financial aspects of science and commodification of scientific knowledge might communicate a rather pessimistic image of the scientific enterprise. Choosing to delve into them has to take into consideration children's developmental levels, time considerations and the extent to which the episode is useful for understanding concepts and connections between science and society.

It could be argued that embedding the expanded FRA categories into the curriculum might increase the cognitive demands on students and push the content beyond their reach. However, "cognitive development and educational psychology are converging on important conclusions that address policy concerns about STEM illiteracy. All show that we can teach science in a meaningful and better way, much earlier than we have—and that even preschool children have some relevant abstract abilities" (Vandell, Gelman, & Metz, 2010, p. 26). We extend the logic of this argument to maintain that when appropriate epistemic and social aspects are intertwined with the cognitive ones, they provide a stronger context and deeper meaning to the learning experience. When elements of the cognitive-epistemic and social components of science are infused into the curriculum in a developmentally appropriate way, children will most likely understand them. But this entails reconceptualizing what is developmentally appropriate in light of emerging research (Metz, 2009). Several studies demonstrate how skillful accessing of students' cognitive resources offers promising opportunities for developing strong epistemic and cognitive understanding of concepts (e.g., Elby & Hammer, 2010; Magnusson & Palincsar, 2005). Developing a learning progression for components of the expanded FRA can eventually guide the development of performance expectations for K-12 students (see NGSS Lead States, 2013, pp. 5–6).

Designing curriculum along the FRA dimensions proposed in this paper includes recognition of the pedagogical demands that FRA might place on teachers. Teachers would need to know a lot more about how the expanded FRA categories are contextualized in relation to the curriculum standards in their own countries. Teachers need to have access to additional information, practical resources and suggestions on how to promote more holistic discussions about nature of science. But we consider this to be a normal task that follows the introduction of new frameworks and a central component of designing educative curriculum materials that are intended to promote teacher learning using the five design heuristics recommended by Davis & Krajcik (2006). We advocate having high expectations from teachers and believe in their ability to embrace challenging curricular and instructional content as part of their ongoing professional development.

An educative curriculum that incorporates the expanded FRA ideas "will promote learning among some teachers and may promote the development of a disposition toward reflection among others. In a best-case scenario—with curriculum materials accompanied by other continuing professional development—incorporating educative elements into the materials should increase the learning outcomes over and above improvements resulting from the professional development alone." (Davis & Krajcik, 2005, p. 4). In the end, nothing guarantees that teachers will follow suggested curriculum *pathways*. But educating them about possibilities through these materials is more likely to help them develop more informed ways of addressing NOS, than would be the case without access to such materials. The suggested pathways for addressing NOS provide options with built-in flexibility that allows selective choice of ideas to be highlighted depending on time, goals, as well as relevance to student context, or current issues.

In practical terms, an educative curriculum that develops components of the expanded FRA enables teachers to draw on existing resources pertaining to each of its categories and to seek additional resources from current events or local communities. When internalized, the incorporation of these ideas is expected to flow out of planned inquiries into scientific practices, or discussions on how scientific knowledge is impacted by financial and other sociocultural factors. Specific probes and supplements to activities can be added that promote the metacognitive thinking about these issues. Less important activities can be removed.

7 Conclusions

In summary, we propose the expanded FRA as a practical conceptual tool to organize the systematic infusion of important facets of nature of science into the curriculum. Elsewhere (Erduran & Dagher, 2014a) we provide detailed justifications for each of the 11 categories of the FRA Wheel and envision how its various components can be implemented. Such level of elaboration is impossible to compact within the limited confines of this article. The elaborate account offers "images of science"; a collection of relevant images that enhance discussions around nature of science and that can be used as heuristics for organizing curriculum and instructional sequences. We also offer a detailed vision for how these images might be articulated in relation to relevant content vertically and horizontally in the K-12 curriculum.

The expanded FRA to NOS approach discussed in this paper focuses on the justification and presentation of its conceptual elements. However, the practical utility of the expanded FRA have been evident in the use of this framework to examine a curriculum policy vision (Dagher, 2012), to analyze curriculum policy documents in the USA (Erduran & Dagher, 2014a) and Turkey (Kaya & Erduran, 2015) and to review a curriculum policy draft in Ireland (Erduran & Dagher, 2014b). Discussions of the expanded FRA have been of interest to interdisciplinary science teaching faculty in higher education (Dagher, 2015) and have been disseminated to K-12 teachers (Erduran, in press; Erduran, 2015). The scientific practices component of the FRA Wheel has been incorporated into a preservice education program in Turkey (Erduran et al., 2015) and disseminated in professional development for science teachers in Turkey in December 2014 and Lebanon in October 2015 (Dagher et al., 2016). Teacher educators have documented their teaching experiences with preservice elementary teachers using the visual heuristic on scientific practices, developed as part the FRA categories (Saribas & Ceyhan, 2015). An analytical tool based on the entire FRA approach is also being used to investigate NOS coverage in textbooks (BouJaoude, Dagher & Refai, 2016). These examples of applications to curriculum and textbook analysis as well as infusion in preservice and inservice teacher education contexts illustrate the empirical power of the expanded FRA in informing and transforming science education.

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