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Contributions of the Family Resemblance Approach to Nature of Science in Science Education

A Review of Emergent Research and Development

Sibel Erduran[1,2,3] • Zoubeida R. Dagher[4] • Christine V. McDonald[5]

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Abstract
The emergence of the Family Resemblance Approach (FRA) to nature of science (NOS) has prompted a fresh wave of scholarship embracing this new approach in science education. The FRA provides an ambitious and practical vision for what NOS-enriched science content should aim for and promotes evidence-based practices in science education to support the enactment of such vision. The present article provides an overview of research and development efforts utilizing the FRA and reviews recent empirical studies including those conducted in preservice science teacher education as well as studies utilizing FRA to analyze NOS representations in curriculum documents and textbooks. The article concludes with implications and recommendations for future research and practice.

1 Introduction

A substantial body of research has been conducted on NOS over the past half century. Great strides in understanding students' and teachers' conceptualizations of NOS-related content have been gained by NOS researchers, with a variety of theoretical and methodological approaches utilized in previous studies. Over the past 25 years, the dominant approach to NOS (commonly referred to as the "consensus view" of NOS) posits that a set of NOS tenets have been developed that are agreed upon as being suitable for K-12 students to learn, and for teachers to implement in school science education. However, the consensus view of NOS has been subject to criticism on the basis of a range of limitations. For instance, Dagher and

✉ Christine V. McDonald
c.mcdonald@griffith.edu.au

[1] Department of Education, University of Oxford, Oxford OX2 6PY, UK

[2] The Norwegian Centre for Science Education, University of Oslo, Oslo, Norway

[3] College of Teacher Education, Zhejiang Normal University, Zhejiang, China

[4] School of Education, University of Delaware, Newark, DE 19716, USA

[5] School of Education and Professional Studies, Griffith University, Mount Gravatt, QLD 4122, Australia

Erduran (2016) argued that a more comprehensive and inclusive framework is needed. The authors draw attention to the need in science education of using classes of ideas rather than simply disconnected and disparate ideas about NOS. Alternative approaches have emerged including whole science (Allchin 2011), features of science (Matthews 2012), and the family resemblance approach (FRA) (Erduran and Dagher 2014a; Dagher and Erduran 2016; Irzik and Nola 2014). Relative to alternative accounts of NOS in science education, FRA is a broader and more inclusive account. For example, it is inclusive of the "Whole Science" ideas represented in Allchin's (2011) account of NOS. For further discussion on the comparison of FRA with other NOS perspectives, see Dagher and Erduran (2017).

The FRA views NOS as embodying a set of aims and values, practices, methodologies, and social norms that are worthy of inclusion in the science curriculum and is based on a theoretical rationale proposed by philosophers of science Irzik and Nola (2014) whose work in turn was based on Wittgenstein's. The idea of a family resemblance with respect to science is based on an understanding that all disciplines of science share certain characteristics; however, none of these characteristics can define science or demarcate it from other disciplines. Irzik and Nola (2014) presented the example of observation (i.e., human observation or observation 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. The same applies to other practices such as inferring and data collection, whereby these are shared by science disciplines, but their use is not necessarily limited to them. As such, FRA highlights both the similarities and differences among scientific disciplines and provides a coherent approach whereby domain-general and domain-specific aspects of NOS can be captured, acknowledging the characteristics that disciplines share as well as those that make them unique.

In this article, we review the background on FRA since its introduction into the science education research literature through Irzik and Nola's original publication (2011a, b), which initially focused on scientific activities, aims and values, methodologies and methodological rules, and products of science. In a later account, Irzik and Nola (2014) broadened the FRA discussion to include the social-institutional dimensions of science. Subsequently, Erduran and Dagher's (2014a) book extended and applied FRA in science education. A significant aspect of Erduran and Dagher's (2014a) work included, among other things, expanding the realm of social-institutional categories to include political, financial, and organizational aspects, and introducing visual representations that can serve as pedagogical and analytical tools for the purposes of science education. Considering how abstract and complex NOS ideas can be, such educational adaptations have been a welcome addition to the research program on NOS in science education. In this paper, we briefly review the background to FRA and subsequently focus on some examples from recent applications of FRA in science education to draw out some emerging empirical themes and to illustrate the contributions of FRA to NOS studies.

2 Background on Family Resemblance Approach to Nature of Science in Science Education

In exploring alternative frameworks on NOS, Irzik and Nola (2014) based their notion of family resemblance on Wittgenstein's work arguing that it provides a "more comprehensive and systematic" approach (Irzik and Nola 2014, p. 1000). The advantage of using the FRA to characterize a scientific field of study is that it identifies a set of broad categories to address a variety of shared and distinct features that characterize the sciences. This is particularly useful in science, where subdisciplines may share common characteristics, but none of these characteristics can define science or demarcate it from other disciplines.

FRA conceptualizes science as a cognitive-epistemic system and as a social-institutional system. The analytical distinctions that Irzik and Nola made are meant to "achieve conceptual clarity, [and] not [serve] as a categorical separation that divides one [dimension] from the other. In practice, the two constantly interact with each other in myriad ways" (Irzik and Nola 2014, p. 1003). Science as a cognitive-epistemic system encompasses processes of inquiry, aims and values, methods and methodological rules, and scientific knowledge, while science as a social-institutional system encompasses professional activities, scientific ethos, social certification and dissemination of scientific knowledge, and social values.

Within the cognitive-epistemic system, Irzik and Nola (2014) discussed four categories described briefly as follows. The processes of inquiry considered in this scheme refer to types of activities that are rather familiar to science educators. They include activities like "posing questions (problems), making observations, collecting and classifying data, designing experiments, formulating hypotheses, constructing theories and models, comparing alternative theories and models" (Irzik and Nola 2014, p. 1007). Aims and values refer to a set of aims in the sense that the products of scientific activity are desired to fulfill them. They include some obvious ones "such as prediction, explanation, consistency, simplicity and fruitfulness" (Irzik and Nola 2014, p. 1007). Aims also include viability, testability, and empirical adequacy that function both as aims and values, and at times they also function as criteria that play a significant role in theory choice.

Methods and methodological rules refer to the variety of systematic approaches and the rules that scientists use to ensure that these methods yield reliable knowledge. Included in these methods are different strategies such as inductive, deductive, and abductive reasoning. Equally important to the methods are the set of methodological rules that guide their use. Examples of methodological rules are such statements as "other things being equal choose the theory that is more explanatory," "use controlled experiments in testing casual hypotheses," and "in conducting experiments on human subjects always use blinded procedures" (Irzik and Nola 2014, p. 1009). Scientific knowledge refers to the "end-products" of scientific activity that culminate in "laws, theories, models as well as collection so observational reports and experimental data" (Irzik and Nola 2014, p. 1010). Reference to the end products is focused on the epistemic and cognitive aspects of these entities, how they become established, and what differentiates them from one another.

Within the conception of science as a social-institutional system, Irzik and Nola (2014) offered four categories that expanded what they had initially proposed as one social context category (Irzik and Nola 2011a, b, July). Science as a social system highlights professional activities, social and ethical norms, community aspects of science work, and the relationships of science with technology and society. Irzik and Nola noted that these categories are not exhaustive and that this may not be necessarily the best way to describe the social aspects of science. The shift in their conception from focusing on epistemic categories (2011a, b), to adding one category of social context (2011a, b, July) to describing four categories embedded under science as a social-institutional system (2014) creates more balance between the cognitive-epistemic and the social-institutional dimensions of science. The four categories under the social-institutional dimension are the following:

- Professional activities refer to activities that scientists perform in order to communicate their research, such as attending professional meetings to present their findings, writing manuscripts for publications, and developing grant proposals to obtain funding.
- Scientific ethos refers to the set of norms scientists follow in their own work and their interactions with one another. These include particular norms (i.e., universalism, organized skepticism, disinterestedness, and communalism).
- The social certification and dissemination of scientific knowledge refer to the peer-review process, which tends to work as a "*social quality control* over and above the *epistemic control* mechanisms that include testing, evidential relations, and methodological consideration" (Irzik and Nola 2014, p. 1014).
- The social values of science refer to those social values such as "freedom, respect for the environment, and social utility broadly understood to refer to improving people's health and quality of life as well as to contributing to economic development" (Irzik and Nola 2014, p. 1014).

The eight categories are not mutually exclusive entities but are complementary in the sense that they target different dimensions of the scientific enterprise. They are identified in separate categories to allow a more detailed analysis. Given the complexity of the scientific enterprise, it is helpful to disentangle some of its components, especially those that constitute commonalities across different domains. Irzik and Nola (2011a, b, 2014), July) noted that even though the processes, aims and values, methods and methodological rules, knowledge claims, and the four aspects of the social institutional system may differ across science domains, there is enough resemblance along these categories within and across domains that make them recognizable as scientific.

Irzik and Nola (2014) described the Family Resemblance Approach itself as follows:

> Consider a set of four characteristics {A, B, C, D}. Then one could imagine four 440 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 generalized 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. In what follows we will employ this polythetic version of family resemblance (in a slightly modified form) in developing our conception of science. (Irzik and Nola 2014, p.1011).

They then proceeded to argue that there are some characteristics common to all sciences and some others that are rather specific to particular sciences. For example, sciences 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) gave the example of astronomy and earth sciences. These domains cannot possibly rely on experiments as celestial bodies cannot be manipulated. Likewise, earthquakes cannot 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 randomized trials as D, I, E, P, H and T, respectively. Then we can summarize 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 and Nola 2014, p. 1013)

In summary, the FRA provides an account where the domain-general and domain-specific aspects of science can be articulated. In their elaborate account of FRA, Erduran and Dagher (2014a) introduced new categories named as "financial systems," "political power structures," and "social organizations and interactions" to provide further nuance to the social context of NOS. These authors have also synthesized relevant perspectives from science education research to illustrate the relevance of FRA for science education. Furthermore, Erduran and Dagher proposed a set of visual representations to facilitate the communication of fairly abstract and complex philosophical ideas in ways that can be useful for science educators. In the next sections, we review educational adaptations of FRA to illustrate not only its relevance but also its utility in conducting empirical research.

3 Applications of the FRA Framework in Science Education

The FRA to NOS (Erduran and Dagher 2014a) synthesizes philosophical perspectives offered by Irzik and Nola (2014) with evidence from science education research to suit the purposes of science education and can be considered both a theoretical and a methodological approach. The approach asserts the importance of addressing critical cognitive, epistemic, and social–institutional aspects of science in school science. A total of 11 NOS categories are grouped under two dimensions, (1) cognitive-epistemic system encompassing: aims and values, scientific practices, methods and methodological rules, scientific knowledge, and (2) social-institutional system encompassing: professional activities, scientific ethos, social certification and dissemination, social values of science, in addition to the three categories proposed by Erduran and Dagher (2014a), which are social organizations and interactions, political power structures, and financial systems (refer to Table 1 for further elaboration of NOS categories).

Each of these categories expresses classes of ideas about science that are not meant to be exclusive and distinct. Rather, they relate to one other in a dynamic and interactive fashion. The 11 components of the framework are represented by the FRA Wheel which provides an image of science as a holistic and dynamic system that visually represents the relationship between its components as parts of a larger whole. Boundaries between the categories are porous (represented by dotted lines), to indicate that none of the categories are sheltered from one another's influence regardless of the location they occupy on the "FRA Wheel" (refer to Fig. 1).

The bare description of the FRA categories obscures the framework's tremendous pedagogical and practical utility for guiding curriculum development and instruction. The aim of the FRA is not to teach students individual NOS aspects, but instead to present NOS holistically in a contextualized manner. The framework potentially allows teachers, curriculum developers, and teacher educators to highlight particular NOS aspects that are most relevant to the content under study and does not require coverage of all NOS aspects in all contexts. The

Table 1 Cognitive-epistemic and social-institutional NOS categories (adapted from Erduran and Dagher 2014a; McDonald 2017)

Cognitive-epistemic system dimensions	
Aims and values	The scientific enterprise is underpinned by adherence to a set of values that guide scientific practices. These aims and values are often implicit and they may include accuracy, objectivity, consistency, skepticism, rationality, simplicity, empirical adequacy, prediction, testability, novelty, fruitfulness, commitment to logic, viability, and explanatory power
Scientific practices	The scientific enterprise encompasses a wide range of cognitive, epistemic, and discursive practices. Scientific practices such as observation, classification, and experimentation utilize a variety of methods to gather observational, historical, or experimental data. Cognitive practices, such as explaining, modeling, and predicting, are closely linked to discursive practices involving argumentation and easoning
Methods and methodological rules	Scientists engage in disciplined inquiry by utilizing a variety of observational, investigative, and analytical methods to generate reliable evidence and construct theories, laws, and models in a given science discipline, which are guided by particular methodological rules. Scientific methods are revisionary in nature, with different methods producing different forms of evidence, leading to clearer understandings and more coherent explanations of scientific phenomena
Scientific knowledge	Theories, laws, and models (TLM) are inter-related products of the scientific enterprise that generate and/or validate scientific knowledge and provide logical and consistent explanations to develop scientific understanding. Scientific knowledge is holistic and relational, and TLM are conceptualized as a coherent network, not as discrete and disconnected fragments of knowledge
Social-institutional system dimensions	
Professional activities	Scientists engage in a number of professional activities to enable them to communicate their research, including conference attendance and presentation, writing manuscripts for peer-reviewed journals, reviewing papers, developing grant proposals, and securing funding
Scientific ethos	Scientists are expected to abide by a set of norms both within their own work, and during their interactions with colleagues and scientists from other institutions. These norms may include organized skepticism, universalism, communalism and disinterestedness, freedom and openness, intellectual honesty, respect for research subjects, and respect for the environment
Social certification and dissemination	By presenting their work at conferences, and writing manuscripts for peer-reviewed journals, scientists' work is reviewed and critically evaluated by their peers. This form of social quality control aids in the validation of new scientific knowledge by the broader scientific community
Social values of science	The scientific enterprise embodies various social values including social utility, respecting the environment, freedom, decentralizing power, addressing human needs, and equality of intellectual authority
Social organizations and interactions	Science is socially organized in various institutions including universities and research centers. The nature of social interactions among members of a research team working on different projects is governed by an organizational hierarchy. In a wider organizational context, the institute of science has been linked to industry and the defense force
Political power structures	The scientific enterprise operates within a political environment that influences the direction and use of science. The outcomes of science are not always beneficial for individuals, groups, communities, or cultures
Financial systems	The scientific enterprise is mediated by economic factors. Scientists require funding in order to carry out their work, and state and national level governing bodies provide significant levels of funding to universities and research centers. As such, these organizations have an influence on the types of scientific research funded, and ultimately conducted

suggestive, rather than prescriptive, nature of the approach can enable various stakeholders to make choices regarding how they would like to embed the NOS ideas in the curriculum.

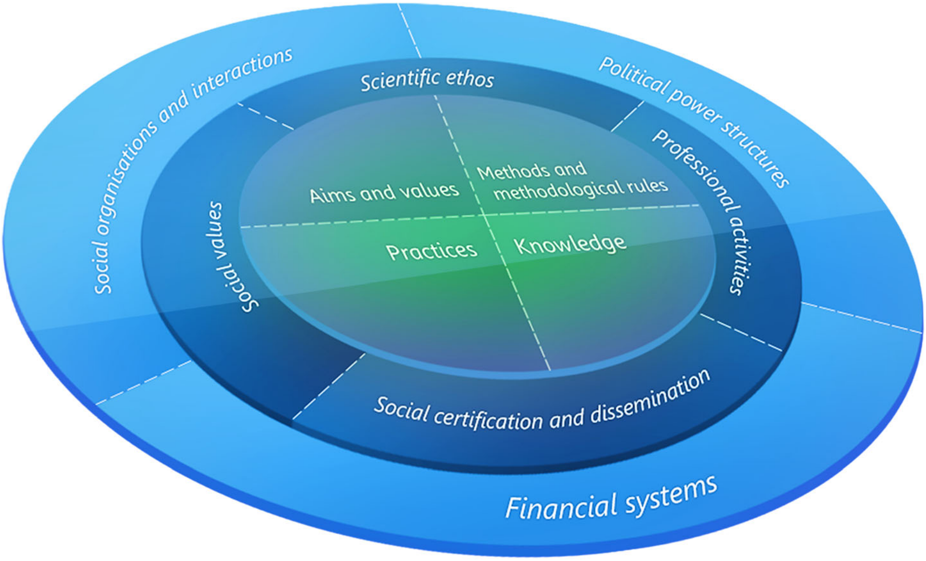

Fig. 1 FRA Wheel: science as a cognitive-epistemic and social-institutional system (Erduran and Dagher 2014a)

The FRA is a sophisticated and comprehensive approach for *framing* NOS-related conversations for science education (Erduran and Dagher 2014a; Dagher and Erduran 2016). From a curriculum perspective, meaningful engagement with the FRA to NOS entails integrating aims and values of science into scientific practices, exploring methods when engaging with practices, alluding to financial systems when these influence the direction of the research, and involving students with metacognitive reflection on classroom inquiries. To support the integration of the different NOS categories, Erduran and Dagher (2014a) proposed a set of visual tools, termed *Generative Images of Science*, that support teachers in guiding student reflection on scientific methods and cultural norms when engaging with scientific practices; discussing the values that guide the choice of research questions, research methods, and explanatory structures; and exploring organizational structures and societal values that influence or undergird scientific activities.

In an effort to distinguish Erduran and Dagher's (2014a) version of the FRA to NOS from that of Irzik and Nola's (2014), several qualifiers have been used in previous work as a shorthand when referring to Erduran and Dagher's (2014a) book-length version of the FRA or its article-length summary (Dagher and Erduran 2016). Terms such as expanded FRA, extended FRA, and reconceptualized FRA to NOS (RFN) have been used. Considering the theoretical ideas on FRA were published in 2014, the timeframe for the uptake and use of FRA in science education has been fairly limited. As expected when working with new ideas, evidence about the effectiveness of the FRA is still emerging. This article provides an overview of research and development efforts that utilize the FRA to NOS including curriculum and textbook analysis, and teacher education.

4 Applications of the FRA

This section provides an overview of empirical work utilizing the FRA in science education. This work includes completed doctoral (e.g., Cullinane 2018) and master's (e.g., Akgun 2018;

Alayoglu 2018; Cilekrenkli, 2019; Karabas 2017) dissertations, as well as analyses of curriculum documents (e.g., Erduran and Dagher 2014b; Kaya and Erduran 2016; Yeh, Erduran and Hsu, in press) and textbooks (e.g., BouJaoude et al. 2017; McDonald 2017). Practical resources including instructional materials (e.g., Erduran et al. 2019a, b) and professional development resources (e.g., Erduran and Kaya 2019; Erduran et al. 2016) have been produced based on the FRA. FRA has been used by practising secondary teachers to plan, teach and evaluate lessons (e.g. Cilekrenkli 2019). FRA has also been used as an analytical framework in order to investigate university students' understanding of NOS (e.g. Akgun 2018).

A significant strength of the FRA framework lies in is its versatility and potential for making *conceptual* contributions to related areas of research in science education. For example, the manner in which the nature of science and nature of religion are conceptualized plays a significant role in shaping the dialog between science and religion in the public sphere. This dialog influences whether some scientific theories are included in the curriculum (such as the theory of evolution) and whether they get taught or ignored in practice. Dagher (2017) used the categories of the FRA (Erduran and Dagher 2014a) to systematically analyze distinct features of science and religion as two different ways of knowing. She illustrated how FRA categories can be used to help disentangle religious claims from scientific arguments and navigate perceived areas of conflict between scientific theories and religious accounts. She proposed that this line of work is aligned with ongoing efforts in the philosophy of science to address viable approaches to the demarcation problem (e.g., Hoyningen-Huene 2013) and is motivated in science education by the need to approach learning from a culturally sensitive and harmonious perspective.

In another context, Dagher (in press) explored how the components of the FRA provide functional tools for bridging current gaps between science education studies focused on NOS and those focused on social justice. She contrasted notions of "cold" or discipline-based and "warm" or community-based notions of NOS, to demonstrate how the FRA can be used to bridge the gap and support teaching science for social justice. Using concrete examples, the author illustrated how holistic NOS frameworks that balance the epistemic and social realms of science, like the FRA (Erduran and Dagher 2014a), lend themselves to supporting rigorous science learning within a social justice agenda, in ways that are not afforded by narrowly-defined epistemic notions of NOS.

Erduran et al. (in press) investigated how the FRA framework can be linked to broader curricular goals related to social justice. Even though enhancement of students' understanding of social justice is thought to contribute to good citizenship, contextualizing social justice in science education remains challenging for teachers because social justice is not conventionally a common feature of science teaching and learning. Although social justice and NOS literatures might share similar themes such as citizenship goals, the precise intersection of these literatures had not been previously investigated. Erduran et al. (in press) drew on theories from political philosophy where they traced the potential overlap of social justice and NOS concepts (e.g., diversity, equity), and provided recommendations for curriculum policy.

A further contribution of FRA has been in the context of visualization of NOS (e.g., Erduran 2017). In a recent study, Erduran and Kaya (2018a) investigated how aspects of NOS such as nature of "scientific knowledge" and "scientific practices" can be represented visually and how they could be used to facilitate teachers' learning of NOS. The authors drew on the *Generative Images of Science* developed by Erduran and Dagher (2014a) to encourage pre-service teachers to visualize the nature of scientific knowledge and practices. Although NOS and visualization literatures have separately been studied extensively, the intersection of these bodies of literatures has been minimal. Incorporating visual tools in teacher education, for instance, is likely to facilitate teachers' own learning, eventually impacting students' learning of NOS. Erduran and Kaya (2018a) provided evidence on pre-service teachers' own visual representations of scientific knowledge and practices including the change in their quality following teacher education sessions.

An emerging contribution of FRA is its capacity to generate methodological and analytical tools either as a collective set of categories or specific instances of categories. Erduran et al. (2019a) used the theme of diversity of scientific methods to investigate chemistry examination papers from high-stakes tests in England. Drawing on Brandon's framework (Brandon 1994) as presented in Erduran and Dagher's (2014a) book, Erduran et al. (2019a) focused on four categories of methods: manipulative hypothesis testing, non-manipulative hypothesis testing, manipulative parameter measurement, and non-manipulative parameter measurement. The items from two examination papers of a leading examination board were classified according to these categories and patterns on the marking were traced. The results indicated that for both papers, non-manipulative parameter measurement was the method assessed at a higher percentage.

In both papers, manipulative hypothesis testing was the category with the lowest percentage of items. Furthermore, the mark allocation was the highest in both papers in the non-manipulative parameter measurement category. The results indicated that there is consistency between the items allocated to each category and the marks allocated to them, although in one paper, there were more marks allocated to manipulative hypothesis testing even though the relative frequency of this category was the lowest in the items. This may reflect an assumption that manipulative parameter measurement is considered to be cognitively more demanding, or it may reflect a perception that is a more valuable methodology, and thus deserving of more marks.

Another example of the utility of the FRA is illustrated in a study by Peters-Burton et al. (2017) who employed an epistemic network analysis methodology (ENA) to re-analyze NOS data, using the FRA framework as an analytical tool. The data were originally obtained from a card sort activity conducted with scientists, and middle school teachers and students, and had been analyzed previously using the consensus view as an analytical tool. By re-analyzing the data using the FRA framework, the participants' statements were re-classified along the FRA's categories. The resulting maps of science ideas and their interconnections revealed completely different and more nuanced patterns than those previously detected. Student and teacher maps possessed no central idea, while scientist maps showed statements that were connected, which implies more coherence among a variety of ideas than in teachers' or students' maps. These findings support using the FRA model for studying scientific epistemology because the empirical evidence reflected more robust, inclusive, and distinctive patterns that were accounted for by the model.

In the next sections, we focus more closely on two areas to illustrate the contributions of FRA in science education. The first concerns the analysis of curriculum policy documents and textbooks using FRA. The second reviews studies on how FRA can inform teacher education and teachers' views of NOS. Considering the pivotal role of the science curriculum in school teaching and learning of science, the identification of how NOS is represented in the curriculum is of utmost importance. Likewise, educating preservice and in-service science teachers to teach conventionally unfamiliar curriculum content such as NOS remains a challenge despite decades of work on NOS in science education.

4.1 Curriculum Policy and Textbook Analysis

Two early studies utilized the FRA to analyze science curriculum policy (Erduran and Dagher 2014b; Kaya and Erduran 2016). Erduran and Dagher (2014b) examined NOS coverage in an Irish draft science curriculum and assessment framework using the FRA. The draft document included a new component on NOS which has been positioned as a central feature of science learning. The application of the FRA was used to highlight where the curriculum could be infused with more detailed representations of NOS, and the NOS categories were examined in unison to present a coherent overall story. Results indicated the current articulation of the various elements of NOS in the curriculum and assessment specification refer to generic and undifferentiated components that do not necessarily build on an overarching topic or story. The authors asserted that students' engagement in science in general and in learning NOS in particular would be enhanced if the various categories are interrelated in meaningful contexts that go beyond disconnected bits of information.

A later study (Kaya and Erduran 2016) investigated the potential of the FRA in facilitating curriculum analysis and in determining the gaps related to NOS in the curriculum in two Turkish science curriculum documents published 7 years apart and then contrasted them with documents from USA and Ireland. This was done to show trends in the coverage of various FRA categories, and help clarify how the adaptations of the FRA could contribute to curriculum analysis and development. Results indicated that in all documents, there was no overall coherence to NOS as a holistic narrative that would be inclusive of the various FRA categories simultaneously. Whilst the authors observed most of the FRA categories in the curriculum policy documents, it was not clear how the categories contributed to a meaningful whole. With respect to the comparative analysis of international curriculum documents from the USA, Ireland, and Turkey, there was limited coverage of the categories of professional activities, financial systems, and political power structures in all documents. The category of social organizations and interactions was present only in the Turkish curriculum, and the scientific ethos category was only present in the Irish curriculum.

More recently, Yeh et al. (in press) used an analytical tool based on FRA for investigating two sets of Taiwanese curriculum guidelines published 10 years apart. The findings show a shift away from the excessive centralization of the cognitive-epistemic system to a consideration of the social-institutional system. Aims and values, which can be viewed as keystones when scientists use them to shape a research progression and adhere them in a science enterprise, were found to increase in number. Scientific knowledge was considered to a lesser extent in the NOS benchmarks, and its specification as a coherent set of theories, laws, and models was not mentioned. The authors proposed modifications to the benchmarks that consider a holistic and progressive approach to NOS. Park et al. (2019) used FRA as a framework for comparing and contrasting constituent disciplines of STEM (i.e. science, technology, engineering and mathematics) as members of a "family" that share particular features but also highlights domain-specificity where particular knowledge and practices are specific to the respective discipline. They conducted a comparative analysis of two influential curriculum standards in the USA, Science for All Americans (SfAA) and the Next Generation Science Standards (NGSS) to examine their coverage of epistemic underpinnings of STEM disciplines.While there were numerous similarities between SfAA and NGSS (e.g., advocating the epistemic aim of "accuracy" in science), SfAA seemed more nuanced in some aspect while NGSS in others. For example, while SfAA is more nuanced in terms of the kind of methodological approaches science utilises (e.g., reference to hypothesis as well asquantitative and qualitative methods), NGSS details the kinds of scientific knowledge interms of theories and laws in a more thorough manner. With respect to a contrast of the reference to technology and engineering, NGSS seems to place more emphasis on engineering design and extensive reference is devoted to engineering practices. A significant variation between the two documents is the reference to practices such as argumentation and modelling. Finally, in the case of NOS, a significant observation is that NGSS does not explicitly refer to the epistemic aims, values and methods of mathematics while there is some reference to these categories in SfAA. There is much more coverage of types of mathematical knowledge such as theories in the case of SfAA while the NGSS is fairly limited in its discussion of the nature of mathematical knowledge.

Two recent studies have utilized the FRA to analyze NOS representations in school science textbooks. BouJaoude et al. (2017) explored representations of NOS in ninth grade science textbooks in Lebanon, which consist of separate volumes titled chemistry, life and earth sciences, and physics. Using an analytical framework derived from the FRA, the authors did not sample lessons or units but applied the analytical framework to the entire content of each textbook to ensure that they were mindful of contextual details and did not miss embedded NOS components. Their findings indicated that none of the textbooks systematically or adequately addressed NOS; however, the coverage of individual NOS categories was found to vary across disciplinary boundaries. The physics textbook failed to address any of the examined NOS categories, whereas the life and earth sciences textbook (which only focused on life science) addressed five NOS categories, and the chemistry textbook addressed four NOS categories. The cognitive-epistemic aspects were more frequently addressed in the life and earth sciences textbook (16 instances), than the chemistry textbook (5 instances), whereas social-institutional aspects were addressed in a similar manner in both textbooks, with social values highlighted in both texts, and five other aspects not addressed at all by either text. The authors demonstrated how the application of the FRA provided a tool for examining NOS representations across disciplines that also enabled them to provide specific suggestions for improving and enriching NOS content.

McDonald (2017) took a slightly different approach and explored four Australian junior secondary textbooks representations of NOS within the topic of genetics. In the case-based analysis of representations of NOS using the FRA, results indicated that NOS was not explicitly addressed within the examined chapters. Multiple, implicit opportunities to consider relevant NOS aspects embedded within the topic of genetics were present; however, the absence of prompts or guiding questions and statements highlighting links to explicit representations resulted in missed opportunities to effectively portray NOS to junior secondary students using these resources. The application of the FRA enabled an in-depth, holistic exploration of how NOS was represented in the topic and identified aspects of NOS highlighted in the various key organizing sections (sub-topics), science content (main narrative), historical and contemporary vignettes, science inquiry activities, and question sets. The FRA enabled particular NOS aspects that are already part of the content under study to be highlighted and did not require all NOS aspects to be included in all contexts.

The two studies that explored NOS representations in textbooks using the FRA reported different advantages to their analysis. The analysis of BouJaoude et al. (2017) enabled them to evaluate the depth of the treatment of NOS ideas and use the knowledge gained to improve weak NOS connections and incorporate neglected aspects. McDonald's (2017) application of the FRA enabled her to determine how the NOS aspects were represented in the topic of genetics, without necessarily requiring that all NOS aspects be included in the chosen context.

This framework may be particularly useful in studies seeking to further examine subtle differences in how individual NOS aspects are represented in science disciplines (e.g., biology, chemistry, physics) and science topics within disciplines (e.g., evolution, periodic table, heat energy).

Both textbook studies using the FRA identified weaknesses in the examined textbooks that echo the general findings by previous textbook studies utilizing other analytical frameworks (see McDonald and Abd-El-Khalick 2017 for a review). However, the present studies differ from previous work in three significant ways in that they (1) explore a broad spectrum of NOS components, (2) utilize an alternative analytical methodology that enables a finer-grained NOS analysis, and (3) adopt an "optimistic" stance to analysis/interpretation to exemplify how weak connections to FRA components can be strengthened in context.

4.2 Teacher Education and Teachers' Views

There are several empirical studies that have integrated FRA in teacher education. We review teacher education projects that have capitalized on the use of this approach in pre-service teacher education. One funded project was conducted in the context of a science teacher education project at a university in Turkey (e.g., Kaya et al. 2019). A total of 15 female pre-service science teachers who were seniors in a Master's level course participated in this project. The teacher education intervention lasted for 11 three-hour sessions. There were two sessions where there was a theoretical introduction to nature of science using Erduran and Dagher's (2014a) book as the main resource. For these two sessions, the pre-service teachers (PST) read the review of literature presented in the first chapter of that book and carried out small-group discussions. Guided by the instructor, the pre-service teachers were encouraged to think about potential applications in teaching practice of the ideas that they were encountering in the readings. Subsequently, 10 sessions were dedicated to aims and values of science; scientific practices; scientific methods and methodological rules; scientific knowledge; and social context of science, with each category lasting two sessions. The first session where each category was discussed was mediated by instruction and was followed up by another session where the pre-service teachers developed lesson materials as a group. Two further sessions were dedicated to the design of an overall lesson resources project carried out by each group where the categories into lesson planning for a sequence of science lessons. Detailed description of the teacher education sessions have been captured in a new book (Erduran and Kaya, 2019). Qualitative and quantitative measures were developed and implemented to trace pre-service teachers' understanding of the nature of science. Some of the results of this project have been reported (Erduran and Kaya 2018a; Kaya et al. 2019). The results suggest that the teacher education intervention reported by Kaya et al. (2019) had a significant impact on preservice science teachers' (PST) views of NOS. The quantitative analysis indicates that this intervention resulted in an overall statistically significant difference in PSTs' views of NOS. When the effect of the intervention was investigated with respect to each category, the results showed that PSTs' views of aims and values of science, methods, scientific knowledge, and social and institutional systems of science improved after the intervention, while there was no significant difference between their pre- and post-views of scientific practices.

The activities covered in teacher education had very particular and focused objectives in unpacking features of categories. For example, in the session for aims and values of science, the PSTs were introduced to epistemic, cognitive, and social aims and values of science. They discussed the related concepts including accuracy, objectivity, and honesty. Regarding the category of scientific methods, they discussed the diversity of methods used in different fields of science. In the social and institutional systems of science session, the PSTs focused on different concepts including financial systems, political power structures, and social ethos. Hence, the outcomes observed were consistent with the intended objectives of the research and development project. The results of the qualitative analysis were in agreement with the quantitative results with respect to the findings from the overall questionnaire, and each category in the questionnaire except for the category of scientific practices, which the PSTs had previously been exposed to through other courses.

Erduran et al. (2018) reported on a particular aspect of NOS, namely scientific practices and how this theme has been integrated into a pre-service teacher education program in Turkey. The authors reviewed the use of Erduran and Dagher’s (2014a) benzene ring heuristic (BRH), which consolidates the epistemic, cognitive, and social aspects of scientific practices into a holistic and visual representation. BRH describes scientific practices in terms of concepts such as data, models, explanations, predictions, argumentation, and social certification. The authors reported results from a funded project that integrated BRH in a preservice science teacher education program in Turkey. Qualitative analysis of preservice science teachers’ representations of scientific practices was described in detail and contrasted pre- and post-intervention that involved training through the use of BRH. The results indicated that in some cases, there was improvement in preservice science teachers’ depiction of scientific practices as being holistic. In a related study, Saribas and Ceyhan (2015) reflected in an auto-ethnographical account on what it meant for teacher educators to learn to teach scientific practices through BRH.

In her doctoral thesis on teacher education based on FRA, Cullinane (2018) designed a series of workshops to introduce Irish pre-service teachers to NOS ideas, such as methods, practices, and social institutional aspects. The study was theoretically underpinned by a NOS model by Erduran and Dagher (2014a). A case study research design was implemented, where four cases were identified to inform how pre-service teachers responded to the NOS teaching and learning. Data collection involved pre-, post-, and delayed post-survey data, audio recordings of the workshops and workshop material, interviews, lesson observations, and lesson plans. In the process of analysis, interview transcripts, surveys, and audio recordings were coded, and themes were extracted inductively and deductively. Findings from the study suggest that the FRA-based framework was useful for improving and maintaining the pre-service teachers’ NOS understanding. The study also traced pre-service teachers’ meta-cognitive knowledge of nature of science using Zohar’s characterization of meta-strategic knowledge (MSK) (Zohar 2006). MSK, a sub-component of meta-cognition, is defined as general, explicit knowledge about thinking strategies. It aids teachers to teach higher order thinking skills which is required for teaching with and about NOS.

The meta-strategic lens used has the potential to provide PSTs with the skills to examine science explicitly and draw attention to NOS in their lessons. The pre-service teachers provided positive reports regarding participation in the workshops and described how their involvement increased their confidence to teach NOS prior to, and during teaching practice. They recommended that the workshops be incorporated into their initial teacher education program, as they present a realistic view that is essential for studying science, a view that is currently missing from their program. However, analysis of the collected data suggests that the pre-service teachers had difficulty integrating NOS into their lesson planning and consequently the explicit use of NOS in their lessons and instructional materials was limited.

In a study focusing on the social-institutional aspects of nature of science, Kaya et al. (2018) investigated Irish pre-service teachers’ perceptions and understandings of how the economic dimensions of science contribute to NOS. While the participants were thinking about science mainly from a scientific knowledge point of view at the beginning, they began to talk about the social context of science during and after the study. Furthermore, the findings showed that there was a significant difference in participants' perspectives in economics of science and entrepreneurship in the context of NOS in both continuous and one-off pre-service teacher education contexts, which were investigated for comparison. The participants were able to use higher-level economics and entrepreneurship-related terminology following the implementation of the intervention.

In the context of new curriculum on NOS in Ireland, Kelly and Erduran (2018) examined pre-service science teachers' views about a particular aspect of NOS, namely the aims and values of science such as objectivity and empirical adequacy. The authors focused on the epistemic, cognitive, and social aims and values of science to provide a broad overview and investigated pre-service science teachers' understanding of them. Qualitative methods were used to highlight two case studies that provide an in-depth record of how pre-service science teachers interpreted aims and values of science. While the pre-service teachers believed that older students were most suitable regarding novel and critical examination aims, they also believed that older students were less likely to value objectivity and honesty. When discussing instruction that highlights how science aims to be novel both pre-service teachers stated that this was something that was more important for older students.

Similarly, when discussing critical examination, one pre-service teacher suggested that giving reasons to justify claims was something that was more suitable for high school students. She indicated that younger students just needed a surface knowledge of science content without validating their reasoning of these concepts. Another pre-service teacher suggested that the pressures of having an important exam in senior cycle encourage students to focus on correct answers, rather than their understanding of science. This, he suggested, causes student to be more biased regarding their experimental work as they want to get results as close to the theoretical values as possible. The study illustrates how aims and values of science as elaborated by Erduran and Dagher's (2014a) framework can be explored in teacher education settings to help preservice discuss competing teaching goals as well as their own assumptions about the purpose of science teaching.

5 Implications and Recommendations for Future Research and Practice

The FRA to NOS shows promise in moving the field of NOS forward. Given the relatively short period of time since the publication of Irzik and Nola's (2011a, b) paper where the idea of the "family resemblance" was first introduced then further elaborated (Irzik and Nola 2014) with subsequent extension and more extensive application to science education by Erduran and Dagher (2014a), the number of studies at this point in time continues to grow. Hence, it is difficult to construct major syntheses based on the current research base. However, new insights into the NOS field have emerged from the set of empirical studies that have utilized the FRA to NOS in the areas of curriculum document analysis, textbook analysis, and teacher education.

Studies have adapted FRA as an analytical tool for investigating curriculum documents and illustrated how this approach can provide a critical lens for evaluating the extent to which curriculum frameworks include the epistemic, cognitive, and social-institutional component of science. The curriculum and textbook analyses in the context of Australia (McDonald 2017), Ireland (Erduran and Dagher 2014b), Lebanon (BouJaoude et al. 2017), Turkey (Kaya and

Erduran 2016) and USA (Park et al. 2019) point to the methodological utility of FRA. In all cases, the documents investigated were found to have significant shortcomings in terms of the coverage of the social-institutional aspects of NOS. The FRA framework points to specific nuances about which aspects of the social-institutional aspects are particularly underrepresented.

In doing so, these studies illustrate how the FRA can be used to identify gaps in draft curriculum documents that can inform conversations about potential revisions. In the case of mature curriculum documents, FRA analysis can inform discussions about how to highlight existing NOS components and introduce missing ones contextually and meaningfully in science curriculum and instruction.

Furthermore, the applications of FRA in teacher education have pointed to its potential as a pedagogical strategy in shaping the content of teacher education. In a book length account of the use of the epistemic categories of FRA, Erduran and Kaya (2019) illustrated in great detail how pre-service teachers' understanding of the aims, values, practices, methods, and knowledge of chemistry can be enhanced in the context of chemistry teacher education. Likewise, in a doctoral dissertation, Cullinane (2018) provided thick description of the impact of a teacher education intervention based on FRA on pre-service teachers' understanding of NOS. In both accounts, the evidence from pre-service teachers' visual representations (i.e., Erduran and Kaya 2019) and verbal accounts (i.e., Cullinane 2018) of NOS suggests a positive and interconnected understanding of NOS.

Regarding textbook analysis, we believe that additional research can help ascertain the effectiveness of the FRA for assessing NOS representations in textbooks both within and across topics and disciplines. Future studies are needed to explore the range of NOS components embedded in individual science topics and disciplines using the fine-grained analysis afforded by the FRA. From this analysis, recommendations for strengthening weak connections to FRA components within the given context can be made to improve science textbooks.

Considering the fact that FRA in science education is a fairly young research program, there is much work still to be done. We propose that future research utilizing the FRA should focus on the following four areas:

- Learning: Investigating learning of students at different levels of education and tracing progression of learning and understanding
- Instruction: Designing and testing exemplary materials to demonstrate how the FRA components can be embedded in science teaching
- Teacher education: Developing and disseminating teaching plans including the FRA components for preservice and in-service teacher education settings especially for programs that do not have specific courses on NOS
- Assessment: Producing and validating assessment tools tailored to different audiences (e.g., teachers, students) as a necessary companion to how the FRA is interpreted, evaluated and applied
- Conceptual advancement: Exploring the FRA's potential to inform a variety of theoretical and practical issues in science education, be it in terms of navigating controversial issues, teaching science for social justice, or developing more sophisticated methods and tools for data analysis

The growing number of studies that have been conducted to-date points to the FRA's utility in analyzing curriculum policy documents, science textbooks, preservice, and in-service teacher education contexts, and establishing bridges across research traditions in science education. For example, the links to social justice (e.g., Dagher in press; Erduran et al. in press) and visualization (e.g., Erduran and Kaya 2018a) literatures are testimony to the versatility of FRA in serving broader goals of science education through NOS. In addition, Couso and Simmaro (in press), Park et al. (2019) and Erduran and Kaya (2018b) have utilised FRA in exploring how STEM education can be improved through epistemic characteristics of the respective disciplines (i.e. science, mathematics, engineering and technology) . We expect that the volume of conceptual and empirical studies on the FRA will continue to grow with the passage of time, providing science teacher educators and researchers with valuable insights about its utility and effectiveness in improving understanding of the nature of science in a variety of contexts.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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