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SI: FAMILY RESEMBLANCE APPROACH

To FRA or not to FRA: What is the question for science education?

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Abstract
Nine years after reconceptualizing the nature of science for science education using the family resemblance approach (FRA) (Erduran & Dagher, 2014a), the time is ripe for taking stock of what this approach has accomplished, and what future research it can facilitate. This reflective paper aims to accomplish three goals. The first addresses several questions related to the FRA for the purpose of ensuring that the applications of FRA in science education are based on robust understanding of the framework. The second discusses the significance of the FRA by highlighting its capacity to support science educators with the exploration of a wide range of contemporary issues that are relevant to how teachers and learners perceive and experience science. The third goal of the paper offers recommendations for future directions in FRA research in the areas of science identity development and multicultural education as well as curriculum, instruction, and assessment in science education.

1 Introduction

Considering the entire thematic issue of *Science & Education* is dedicated to FRA as well as the detailed accounts elsewhere (i.e., Dagher & Erduran, 2016; Erduran & Dagher, 2014a), our coverage will be brief and will serve to set the context for our current discussion. In a nutshell, FRA recognizes that all branches of the natural sciences have shared features that distinguish them from other fields. While the shared features are not fixed, they provide enough resemblance to view these fields as scientific. The FRA can serve multiple purposes, for example, for demarcation to distinguish science from non-science or pseudoscience. However, a key purpose for applying it to science education concerns the potential of its aspects to support reasoning meaningfully about science in disciplinary and societal contexts. FRA accounts for the cognitive, epistemic, institutional, and social aspects of scientific knowledge (Irzik & Nola, 2011) including the financial, political, and

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organizational aspects that impact its production and dissemination (Erduran & Dagher, 2014a). The FRA categories are interrelated, and as a set, provide a comprehensive and multidimensional framework represented in the FRA wheel (Fig. 1) that can be used to guide conversations about nature of science (NOS).

A description of the FRA categories is presented in Table 1. These categories are interrelated and capture nature of science in a holistic way. They are justified and elaborated in our book (Erduran & Dagher, 2014a). The FRA categories are akin to a set of guidelines in a manual that educate and orient teachers towards productively engaging students with contextualized discussions about NOS. In other words, the FRA provides a roadmap to guide and focus discussions about NOS in science education. Applying FRA to NOS is aimed at supporting science learning in context, in line with the humanistic tradition in science education that seeks to situate science in its proper personal, societal, and historical context (Klopfer & Aikenhead, 2022). History, philosophy, and sociology (HPS) of science insights are invoked as appropriate to unpack phenomena, explanations, applications, and implications to personal and societal issues. Marshalling understanding about HPS to support such contextualization requires integrating and explicitly addressing their components in science teaching.

In this reflective paper, we aim to accomplish three goals, each of which is addressed in the paper's main sections. The first is to address several questions that have been raised about the FRA's content and utility following the publication of the original accounts of FRA-NOS in science education (e.g., Dagher & Erduran, 2016; Erduran & Dagher, 2014a; Irzik & Nola, 2011). The purpose of doing so is to pave the way for a more robust understanding of the framework. The second goal is to discuss the significance of the FRA in supporting science educators and researchers with the exploration of a wide range of contemporary issues that are relevant to how teachers and learners perceive and experience science. The third goal is to build on knowledge gained from extant studies and make recommendations for future directions in FRA research.

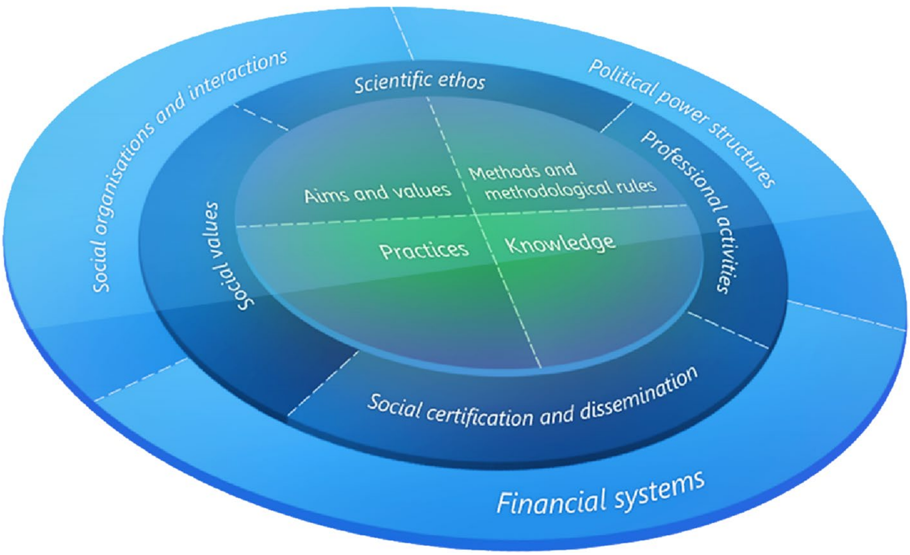

Fig. 1 The FRA Wheel (reprinted from Erduran & Dagher, 2014a, p. 28)

Table 1 Overview of the FRA categories (adapted from Erduran & Dagher, 2014a)

Aspects of science as a cognitive-epistemic system	
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, and rationality
Scientific practices	Science includes 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. Explanations and predictions are mediated by discursive practices involving argumentation and reasoning
Methods and methodological rules	Scientists utilize a range of observational, investigative, and analytical methods guided by methodological rules to generate reliable evidence
Scientific knowledge	Theories, laws, and models (TLM) are interrelated forms of scientific knowledge. As such, scientific knowledge is holistic and relational, and TLM are conceptualized as a coherent network, not as discrete and disconnected fragments of knowledge
Aspects of science as a social-institutional system	
Professional activities	Scientists engage in several 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	Scientific communities are expected to engage in a set of social norms such as scepticism, 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 ensures 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, honesty, addressing human needs, and equality of intellectual authority
Social organizations and interactions	Science is socially organized in various institutions including universities and research centres. The nature of social interactions among members of a research team working on different projects is governed by an organizational hierarchy
Political power structures	The scientific enterprise operates within a political environment that imposes its own values and interests
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 centres

2 Questions About the FRA

Since the publication of our original FRA-NOS account (Dagher & Erduran, 2016; Erduran & Dagher, 2014a), several questions have been raised about it in professional science education settings. Addressing these questions is important because they pertain to the purpose of the FRA to NOS, its content, or how it can be instantiated in K-16 science education. Thus, confronting these questions is necessary to ensure that the assumptions underlying them do not impede efforts to use the FRA to develop instructional materials or investigate research questions related to NOS in formal and informal science education. In this section, we identify six questions and consider their implications.

2.1 Is the FRA Too Philosophical and Theoretical?

The FRA is a multi-faceted framework that has been used to guide NOS content in curriculum and instruction. Far from being abstract, our account of FRA is generative replete with heuristics and visual tools that support NOS-infused curriculum and instruction, assessment as well as research. As argued elsewhere, theoretical accounts can provide much utility to both empirical research and educational practice (Erduran, 2022). To assume that the FRA is too philosophical and theoretical is to risk dismissing it without engaging in its content or considering its implications.

Theoretically grounded accounts offer justified arguments for undertaking principled action. The value of a theoretical/philosophical account can be assessed by its internal coherence and its practical implications. Our development and expansion of Irzik and Nola's (2011) conception of the FRA as an appropriate framework to reconceptualize NOS for science education was driven by growing concern about the limitations of existing NOS accounts (Erduran and Dagher's, 2014a). In our detailed synthesis, we leveraged insights from theoretical and empirical studies in the fields of science studies and science education to justify the FRA's components and implications. The translation of the FRA into educational practice is a research-based endeavour in which every FRA category has deep roots in the scholarship of historians, philosophers, and sociologists of science as well as science educators. In other words, the FRA is not an exclusive philosophical synthesis of HPS of science, but is primarily a science education account informed by science studies.

2.2 Does the FRA Have Empirical and Practical Utility for Science Education?

The question of empirical and practical utility for science education invites reflection on available evidence. There is now a substantial number of reviewed studies that illustrate how FRA has been applied empirically in science education (see Cheung & Erduran, 2022; Erduran et al., 2019). For example, there is an increasing body of evidence about the impact of the FRA on shaping interventions in teacher education (Cullinane & Erduran, 2022; Saribas & Ceyhan, 2015; Voss et al., 2023) and undergraduate science teaching programs (Petersen et al., 2020), using the FRA as an analytical tool for examining STEM curricula and textbooks in different languages (Couso & Simmaro, 2020; Mork et al., 2022; Park et al., 2020; Salem, 2021) and high-stakes assessments (Cheung, 2020), as well as for tracing elementary (Akbayrak & Kaya, 2020) and university (Akgun & Kaya, 2020) students' understanding of NOS. In terms of practical utility, numerous resources have been developed based on the FRA. Some resources are intended for secondary students, (e.g., Çilekrenkli & Kaya, 2022; Erduran et al., 2020), teachers (Erduran et al., 2016), and researchers by way of offering assessment tools (Kaya et al., 2019). A recent study on a small sample of Taiwanese scientists found that their “own views and interpretations of NOS were in line with the conceptual FRA categories” (Wu & Erduran, 2022), thus providing a preliminary level of validation of its categories by professional scientists. Although there is an increasing number of empirical studies and practical resources based on the FRA, more work is needed in this area making applications of FRA a ripe area for future research in science education.

2.3 Is the FRA Too Complex for Teachers?

Current evidence suggests that the FRA is not too complex for teachers. When the FRA is taught to pre-service teachers, findings indicate statistically significant improvement in their understanding of NOS (Kaya et al., 2019). Pre-service teachers in England and Turkey engageddifferently with the various FRA categories (Erduran et al., 2021). More recently, Voss and colleagues (2023) used the FRA as a tool in pre-service teacher education noting that the participants progressed from utilizing inaccurate representations of NOS to inclusion of accurate implicit messages, and finally to explicit reflective instruction. Pre-service teachers’ questioning also progressed toward targeting more specific NOS aspects. Experienced teachers have used the FRA successfully to support the engagement of middle school students with socioscientific issues (e.g., Chaparian, 2020). Taken together, these studies indicate that science teachers possess the cognitive capacity to understand FRA-NOS concepts and the practical ability to integrate them in their teaching. This can be facilitated by the fact that curricula (e.g., Caramaschi et al., 2022) and textbooks (e.g., BouJaoude et al., 2017; Yeh et al., 2022) are already inclusive of some basic elements that can be further developed into more nuanced NOS concepts.

The FRA offers a unique orientation to NOS that requires that teachers seize opportunities to link the science curriculum to meta-level questions such as “what do science practices involve? What makes our claims trustworthy? If scientists disagree on an issue, which view do we trust? Who is behind the “science? What is scientific knowledge being used for?” The FRA categories are not intended to be taught as an abstract set of ideas about science but to be used to contextualize and anchor science learning. Consequently, effective implementation of the FRA-NOS requires supporting teachers’ pedagogical content knowledge (PCK)—as is the case when introducing a new instructional framework because NOS concepts are neither intuitive nor self-evident. Effective NOS instruction will always be delimited by the teachers’ PCK of NOS and access to supportive curriculum materials. Thus there is no inherent reason or empirical evidence that indicates that the FRA is too complex for teachers. A productive path for moving beyond the complexity question is to continue to develop and research FRA-NOS informed curricula and teacher education resources.

2.4 Is the FRA More Cognitively Demanding for Students Than Other NOS Frameworks?

The NOS is a meta-level characterization of science, and hence, some might argue that it may be demanding for students. However, the question of the relative cognitive demand of different NOS frameworks requires empirical investigation. To our knowledge, there have been no empirical accounts where the cognitive demands placed on students by the FRA have been studied or compared to other NOS accounts. It has been suggested that it is pedagogically prudent to start with consensus view (CV) tenets and then move on to the FRA (Kampourakis, 2016). Depending on instructional goals, this approach may be appropriate in some lessons. By the same token, the reverse sequence or indeed a mix of alternative NOS frameworks may potentially be used in teaching and learning. However, it is important to clarify the assumptions about instructional sequences based on different frameworks and what they may address—or not—in students' learning. Erduran and Dagher (2014a) proposed that FRA can be discussed with young students in a developmentally appropriate way. Their stance is supported by growing evidence that children as young as kindergarten (ages 5–6) use both domain-specific and domain-general abilities to reason about observational evidence in biology (Klemm et al., 2020). Additional evidence from 5th grade students (ages 10–11) affirms their ability to learn about experimental methods and understand complex science ideas when they are designed in developmentally appropriate ways (e.g., Kelemen et al., 2014). Consequently, one can hypothesize that embedding relevant FRA-related questions in that same content is likely to further children's understanding of sophisticated NOS ideas.

In discussing the FRA's curriculum application, we envisioned horizontal (across the same grade) and vertical (across different grades) articulation of its components to ensure systemic exposure out of a concern that associating certain aspects of the FRA with specific grade levels or degrees of competence may result in "fragmented or distorted conceptualization of NOS" (Erduran and Dagher, 2014a, p. 174). There is no fundamental reason for why some of the FRA components cannot be addressed with young children. In fact, this approach has already been trialed successfully with elementary children who were introduced to the social-institutional aspects of NOS based on FRA (Akbayrak & Kaya, 2020). For example, a study of 64 female 5th grade students (10–11 years of age) from Turkey was conducted following science teaching based on FRA-informed resources on NOS (Çilekrenkli & Kaya, 2022). Students' understanding of FRA categories was assessed before, after, and two months after the intervention. Mixed ANOVA results showed that the development of students' understanding of NOS from pre-test to post-test in the treatment group was significantly better than their peers in the control group in terms of total and category-based scores except for the aims and values of science and scientific practices categories. Another study with 7th grade students (12–13 years of age) analysed questionnaires, interviews, and discussion transcriptions following an intervention that coupled socioscientific issues with the FRA (Chaparian, 2020). The findings showed that students developed more informed views pertaining to several FRA-related categories such as scientific knowledge, scientific practices, financial systems, and social organizations and interactions, thus demonstrating that students can process FRA ideas meaningfully. Studies that engage students in FRA-informed instructional resources can begin to articulate potential nuances about which aspects of NOS may pose challenges to students and how to address them through improving teaching strategies.

2.5 Does the FRA Offer Anything New to NOS in Science Education?

Some published remarks have questioned the extent to which the FRA offers anything new to NOS in science education. For example, McComas (2020) states the following: "Erduran and Dagher (2014a) establish their view of science through FRA which looks very much like the view of science represented by the elements of NOS recommended by consensus." (McComas, 2020, p. 31). Koponen (2021), on the other hand concludes that, in practice, FRA looks very much like the CV of NOS when he states: "The FRA takes into account the disciplinary variation within sciences but recognizes that different scientific disciplines always have some sets of shared features; there is a family resemblance between and among disciplines. However, in closer look, focusing on how FRA becomes implemented in practical teaching, the outcome appears to be close to consensus NOS." (Koponen, 2021, p. 4).

Both McComas and Koponen are right to state that there may be similarities between the FRA and CV. However, there are sufficiently distinctive features to warrant disagreement with these authors' conclusions. For example, while the CV tenet "scientific knowledge is tentative" can be seen as similar to FRA characterization of scientific knowledge—particularly in relation to "growth of scientific knowledge" and "paradigm shift" as discussed by Erduran and Dagher (2014a)—a significant difference is that the FRA is a meta-level account that is inclusive of many other concepts about scientific knowledge, not only the concept of tentativeness. The FRA scientific knowledge category discusses different forms of scientific knowledge in terms of coordination between theories, laws, and models. The difference is akin to differentiating a forest from the trees. A forest can have different types of trees, such as pine and oak trees, but a forest is much more than a collection of trees as it encompasses biological organisms (e.g., trees, bacteria) and non-biological factors (e.g., soil type, microclimates). It would be misleading to say that a forest is no different from trees when as a meta-level concept, a forest is intended to capture an ecology of entities and relationships. Likewise, FRA is a meta-level account that focuses on relationships among elements such as links between tentativeness and forms of knowledge. Furthermore, FRA category of scientific knowledge itself would relate to other categories such as practices, aims and values, and social certification to name a few. In addition, in our account (Erduran & Dagher, 2014a), the FRA offers a suite of heuristics and visualizations that are novel. This important didactic innovation provides practical tools for comparing different science domains in relation to their common and distinctive features to support teacher and student understanding of NOS.

2.6 Is the FRA Incompatible with the CV Tenets?

While the previous question addresses the novelty of FRA, this question focuses on issues of compatibility between the FRA and CV frameworks. The FRA does not contradict the CV tenets. Rather, the FRA account subsumes them and focuses on *relational* details within and across categories. FRA also considers a wider range of NOS aspects that are not explicit in the CV account, such as political power structures and financial systems. The FRA consists of a meta-level framework that is inherently inclusive of CV tenets. However, FRA also embraces essential tensions about the changing face of NOS across history, contexts, and domains. In this sense, CV and FRA are indeed different.

Comparing CV tenets to FRA categories is like comparing the structure and function of a particular organ to how the structures of multiple organs enable them to function together in a given system within the human body. The specific structures and functions of one organ cannot adequately account for the workings of the entire system. As alluded to earlier, a fair comparison is to compare the CV tenets, focused on nature scientific knowledge, to the one FRA category that encompasses scientific knowledge. At this level of analysis, it is possible to examine similarities and differences. The CV depicts eight ideas about nature of scientific knowledge (NOSK). Take for example tenets that affirm the "tentativeness of scientific knowledge" and "differences between theories and laws." The FRA category of "scientific knowledge" is inclusive of both, as previously indicated. In other words, FRA's knowledge category subsumes these statements as it articulates similarities and differences among theories, laws, and models and describes how emerging evidence can lead to paradigm shifts and/or knowledge growth. At this level of detail, CV and FRA are compatible. What differentiates FRA from CV includes features such as (a) FRA provides an overall rationale for why different domains of science are called 'science' (i.e., the idea of family resemblance), (b) what domain-specific as well as domain-general aspects of science might be (i.e., nature of which science?) as well as (c) the broad range of FRA categories and (d) the holistic approach to considering different aspects of science.

3 Significance of the FRA in Contemporary Science Education

In the previous section, we reviewed some questions about the FRA to pave the way for in-depth discussion about its affordances. In this section, we highlight some of the ways in which this framework can be used to address some contemporary and pressing issues in science education, focusing, in particular, on three aspects of the FRA's social-institutional dimension specifically those of political power structures, financial systems, and social organizations and interactions.

One of the persistent issues facing science learning pertains to the veil of neutrality that is entrenched in school science. The veil of neutrality refers to the narrative that advances science as a primarily objective field of inquiry that uses the scientific method to produce objective trustworthy knowledge. Yet, as the FRA highlights, objectivity of scientific knowledge is mediated through the social-institutional dimensions of the scientific enterprise. For instance, the diversity of scientists' viewpoints and their negotiation of what counts as scientific knowledge and methods may be influenced by factors such as gender and ethnicity. Furthermore, although the myth of one lock-step scientific method has been heavily critiqued by philosophers of science and science educators alike, there remains the issue of presenting science as a detached, value-free enterprise. This image is implicit in traditional science curricula, through their focus on abstract topics, tightly structured inquiries, and limited attention to the social-institutional dimension of science. More progressive settings that incorporate science-technology-society (STS), socioscientific issues (SSI), and justice-oriented approaches aim to centre science content and inquiries around specific student- or community-related concerns, that open up inquiry spaces and in some cases result in tangible actions (e.g., Bencze & Carter, 2020; Calebrese-Barton, 2003; Zouda et al., 2022), without necessarily exploring the social-institutional aspects of science. Applying a FRA-NOS lens to these inquiries can help inform or guide classroom discussions about emerging scientific, and science-community-society related issues (Dagher, 2020).

Explicit discussion of the social-institutional dimensions of the FRA (e.g., social organizations and interactions, and political power structures) is necessary to dismantle the veil of neutrality because its implicit prevalence can have negative impact on participation and representation in science in the short term and influence science research and public trust in science in the long term. We agree with Duarte and Colleagues that "it is necessary to overcome the choice between an education that is supposedly neutral in political and ideological terms and an education that rejects the socialization of scientific knowledge in the name of respecting the multiplicity of culturally rooted voices from within the different oppressed groups present in today's society" (Duarte, Massi, & Teixeira, 2021, p. 1629). In the rest of this section, we discuss more specifically how attentions to the categories of political power structures, social values, social organizations and interactions, social certification and dissemination, and financial (economic) systems are necessary tools for countering the myth of neutrality. Understanding those aspects provides teachers with background knowledge and context not only to teach better science but to improve participation and representation and earn back public trust in science.

3.1 Participation/Representation in Science

In the USA, Black researchers in STEM fields constitute 6% of faculty positions, even though they constitute 13% of the population. The Pew Research Center reports that "62% of Black STEM employees in the United States say they have experienced racial or ethnic discrimination at work, and 57% say their workplaces do not pay enough attention to racial and ethnic diversity" (Forrester, 2020). According to a 2016 report, women make up only 13% of the engineering workforce. Even though women constitute "20% of engineering graduates, (...) it's been estimated that nearly 40% of women who earn engineering degrees either quit or never enter the profession." This situation is attributed, among other things, to a hostile masculine culture that causes graduates to leave the field. Solutions to these issues require major social and institutional effort to retain women and members of various minoritized groups (Silbey, 2016). Changing that culture requires systemic policy changes as well as educational interventions. Focusing on the latter, K-16 science education and informal science programs have an important role because they involve a larger cross-section of individuals who may feel excluded from science, either because of the decontextualized way in which it is taught or due to the prevalence of unchecked cultural stereotypes about who can or cannot be a scientist. Because it recognizes through its social-institutional dimension that issues such as gender, ethnicity, and race are part and parcel of the scientific enterprise, the FRA inherently acknowledges the need to involve more diverse student populations in science learning to improve their participation and representation in civic discourse and in science-related careers.

Furthermore, as discussed earlier, the objectivity of science, in a non-absolutist sense, is not contingent on the "inclusion of intersubjective criticism but in the degree to which both its procedures and its results are responsive to the kinds of criticism described" (Longino, 1990, p. 76). The inclusion of intersubjective criticism and responsiveness is strengthened by the degree of diversity of participating scientists. This is particularly important for countering implicit bias and for understanding many of the problems and proposed solutions that affect members of minoritized communities differently. Even though the diversity of scientists has improved compared to previous decades, some fields (e.g. engineering and computer science) have not caught up with the gender and ethnic imbalance. A United Nations Educational, Scientific and Cultural Organization (2021) report based on data collected in 2018 states that, "globally, women have achieved parity (45–55%) at thebachelor's and master's levels of study and are on the cusp at PhDlevel (44%) but the gender gap tends to widen as they pursue their career". The report adds that "in academia, female researchers tend to have shorter, less well-paid careers. Theirwork is underrepresented in high-profile journals." (p. 108). A recent documentary demonstrates that sexual harassment and gender inequality are as prevalent in science in the USA as they are in popular and corporate cultures (Shattuck & Cheney, 2020), sounding a clarion call for change.

Exposing students to different ways of doing science and to diverse scientist role models can play an important role in encouraging all students, especially members of underrepresented groups, to see themselves as potential scientists—for as Marian Wright-Edelmen says, "it's hard to be what you can't see." Because identifying contributions of women in the historical record itself tends to be challenging because of systemic bias that has elevated the contributions of male scientists and overlooked the contributions of female scientists, teachers will have to search for existing role models within and outside their own communities to challenge student tendency to envision a scientist or an engineer as a stereotypical kind of person, that is very different from themselves. A good example that students might find fascinating is that of Nalini Nadkarni who studies canopies and engages the public with science outside traditional science education venues (Nadkarni, 2009; National Science Foundation, 2007). Realistic stories can help contextualize scientists' experiences within an enterprise that is subject to some of the same moral triumphs and failings of the general society. Discussing historical facts and resisting the appeal of overly heroic and stereotypical accounts (Allchin, 2003; Metz et al., 2007) enable teachers to create opportunities that help female and minority students understand why there are not too many people like them in science and learn that this is a societal and not a genetic artifact.

The FRA acknowledges links between scientific knowledge growth and development and the institutional barriers to participation, be it due to conflicting value systems (among participants, within institutions, or due to stereotypical views about who is fit to be member of the community). Teacher awareness of equity and justice issues in science is central for engaging students with empowering inquiries and reflective NOS discussions that support science identity development and sense of agency.

3.2 Trust in Science

The FRA's inclusion of scientific aims and values, social values of science, political power structures, methodological rules, and ethos can help guide discussions about science-society issues such as trust in science. The issue of trust in science is not new, but it came to the fore during the recent encounters with questions about COVID-19 mitigation and compliance with public health policies. Concerns about the impacts of climate change on environmental degradation and demands for policy changes have been met with varying degrees of public resistance despite their urgency. Both matters have become highly politicized creating confusion about the facts and their implications (personal, economic, global). Such framing of both issues that focuses purely on the science and ignores competing political interests is unlikely to be effective in providing adequate insight necessary for supporting understanding and decision making. This framing protects the perceived neutrality of scientific knowledge, creating tensions that need to be resolved and placed in their proper context.

One familiar example of selective values influencing research on infectious diseases is the case of AIDS (Aizenman, 2019) in which research on treatments was painfully slow and unresponsive to the staggering rise in affected cases at the time prompting heroic efforts of citizens demanding committing adequate research funding. The case of initial funding for AIDS research stands in sharp contrast with the overly generous funding allocated to researching and finding treatments and vaccines for COVID-19. Discussing the epistemic and social values of science as highlighted by the two dimensions of the FRA allows critical examination of how they impact research funding priorities. Teachers' and students' development of a nuanced understanding of NOS in societal contexts is likely to reduce, rather than increase the risk of dismissing scientific activity as merely political.

In some public debates involving scientific findings, politically motivated objections tend to interfere with public health recommendations by sowing doubt in the presented evidence. A familiar case pertains to how the claim that smoking causes cancer was fought for almost five decades on political grounds financed by special interest agents (i.e., tobacco companies) by attacking evidence for causation as inconclusive while deliberately hiding incriminating scientific evidence that they possessed from the public (Cummings & Proctor, 2015; Oreskes & Conway, 2010). By casting doubt on scientific findings under the pretence of failure to produce indisputable evidence, action intended to address the negative impact could be suppressed. Climate change in another case in point (Oreskes & Conway, 2010). A primary task for science teachers and curricula is to support students' functional science literacy that includes the ability to distinguish legitimate science from disinformation and special interest science (Allchin, 2021).

Violation of methodological rules and social values leads to bad science and serious harm. For example, sex exclusion bias in pharmacological studies results in adverse side effects for women (Fang, 2021). Male-based bias in the design of car safety studies puts female drivers or front-seated passengers at a higher risk for serious injury or death than their male counterparts (Barry & Bergmann, 2019). Violation of social values and ethos though intentional neglect of basic standards of ethical treatment of human subjects is perhaps most discussed in the case of the Tuskegee untreated syphilis in Black males. The direct harm inflicted by this study is not limited to the participants and their immediate families. It has affected the health outcomes of Black males in the broader community. It is estimated that the resulting distrust between older Black males and the medical community accounted for "approximately 35% of the 1980 life expectancy gap between black and white men and 25% of the gap between black men and women" (Alsan & Wanamaker, 2018, p. 407).

The FRA categories of political power structures, financial systems, and social organizations and interactions provide a vision for teaching and learning of science where the source of "science" claims, and their connections to verified expertise, funding sources, and organizational affiliation (hidden and public) are closely scrutinized. Avoiding discussion of the failings of scientists/science, where appropriate, is another way to preserve the myth of neutrality. Acknowledging that such failings took place because some scientists violated scientific ethos (of not harming living things or the environment), their hidden biases ran unchecked by the scientific community, or they engaged in willful misconduct. Egregious acts by scientists have contributed to violating public trust in science. This in turn interferes with compliance with public health directives—as was particularly noted in relation to the lower COVID-19 vaccination rates among minoritized populations. Addressing public distrust requires acknowledging not covering up wrongdoing; debunking disinformation campaigns; and appreciating the complex relationship between knowledge, attitudes, and actions. Appealing to rational thinking through focusing on facts/evidence alone has not been adequate to change conceptions even about relatively tame science topics (Pintrich et al., 1993). It is less likely to be effective at addressing the emotionally charged causes that had led to public distrust in science, without discussing those in context.

Regaining trust in science is a complex process in which school science can play a modest but important role. By dismantling the veil of neutrality, students are better able to make sense of the information they access. For example, students need to understand the science of COVID-19, and implications for prevention though masking and vaccination. But this is not enough. They need to understand the rapidly changing knowledge in this particular case in terms of its immediate and latent impact on policy decisions, set within broader societal considerations. When editors of the prestigious science journal *Nature* were urged to "stick to the science" during COVID-19, an onslaught of opinions ensued, resulting in three podcasts for the lay people to understand how science and politics are related (Howe, 2020). Several experts in science studies, history and philosophy of science, and science communications weighed in. Because their views are just as relevant for scientists and members of the public that include teachers and students, we highlight some of the arguments they presented for making explicit links between science and society. Bruce Lewenstein, a historian of science who is an authority on public communication of science and technology at Cornell University, states:

> …. the world would be a better place if more people had access to the kind of reliable knowledge that science produces. In order for that to happen, people have to have a much better understanding of what science is. And I do not mean a specific content of science, I do not mean an idealized hypothetico-deductive method of science. I mean, the complex social reality of how science has produced. The fact that politics is deeply ingrained in how science gets funded. The fact that competition between research groups is not particularly different than competition between football clubs. That human emotion drives many scientists, that scientists choose problems based on particular concerns. If you talk to cancer researchers find out how many of them got into the field because someone in their family had cancer. Right? They didn't choose this at random. They chose it because this is a field that matters to them.

In this excerpt, Lewenstein specifies those elements of nature of science that are important for a better understanding of science. He captures at least four of the FRA's social-institutional categories: political power structures, financial/economic systems, social organizations and interactions, and the intersection between personal and scientific values. Furthermore, Chiara Ambrosio, associate professor of history and philosophy of science, University College London, dismantles the aura of neutrality that is attributed to scientists by bringing out their human qualities that include their political and scientific orientations:

> Scientists are not just these neutral characters that kind of levitate like ghosts in the corridor of scientific institutions, they're actually like human beings with their own political convictions with their own political ideas. And however objective you will try to be, of course, you will not even start the research program, if you don't sort of believe in what that means to you from a political as well as from a scientific point of view.

The political power structures that are internal and external to science are often associated with funding priorities and organizational privilege. We believe that explicating how they relate and work together does not undermine but facilitate trust in science. By avoiding conversations with students about these issues, we lose an opportunity to leverage rich NOS understandings to reflect on a rapid cycle of scientific knowledge development that is affecting how they manage their actions to keep themselves and their communities safe. If they do not reflect critically on these issues in school, they are not likely to acquire the reflective skills they need to navigate the barrage of science disinformation they encounter on social media and favourite newsfeeds.

In summary, we made the case that discussing elements of the social-institutional dimension of science as framed from the FRA perspective can help dismantle the myth of neutrality that hamper participation and trust in science. Creating opportunities for reflecting on learning about scientific aims and values, scientific ethos and social values of science, methodological rules, and social certification can help pinpoint the specific issues that contributed to the moral failings of science and reduce some of the obstacles that some students may experience when learning science or considering a future STEM career. The FRA framework provides a useful tool for raising teacher awareness about their power to remove barriers from participation and gain courage to engage students in bold conversations about science. Such conversations may potentially create perplexing questions for teachers. For example, to what extent ought some of the negative actions of scientists be shared with students, and at what age? What are the risks of sharing some of the less flattering aspects of science (e.g., cases of scientific misconduct, or harm)? What to do if the discussion runs out of control? What if the discussion yields the opposite outcome? These issues are well captured by Alves (2020) who notes "that by admitting that scientists are not neutral actors in the pursuit of knowledge, they risk their credibility, giving leeway to science deniers, anti-vaxxers, climate crisis deniers and pseudoscientists. This is a valid concern that even more justifies discussions among the natural scientists about the philosophical implications of their work." (p. 1). Likewise, this concern matters for science educators, given that the objectivity of science is challenged regularly—requiring a nuanced approach to NOS which can be facilitated through discussing the interrelated dimensions of the FRA. Avoiding conversations around these issues in school science abdicates responsibility for equipping students with powerful NOS tools that help them navigate public discourse around science-related issues.

4 Future Directions

A fair measure of the utility of a framework in any field is its ability to generate new research questions and productive ways of exploring relevant problems of practice and contribute to their understanding in unique and powerful ways. The empirical studies that used the FRA referenced in this paper and in a recent review (Erduran et al., 2019) have contributed useful knowledge to K-16 science education. Additional large scale studies in these areas are needed for identifying instructional strengths and challenges and improving teacher and student understanding of NOS. Some researchers, however, have ventured outside the typical use of the FRA. In one study, researchers investigated teachers, students, and scientists' views about the nature of the scientific enterprise using the FRA and epistemic network analysis methodology to reveal markedly different NOS profiles among the three groups of participants (Peters-Burton, Dagher, & Erduran, 2023). In another, researchers used the FRA to develop a nature of scientist model that describes how scientists get socialized into epistemic cultures within their immediate communities (Mohan & Kelly, 2020). In a third study, researchers used the FRA to analyse elements of nature of science in public tweets about COVID-19 during the first six months of the pandemic and found that most tweets alluded to multiple FRA categories (Bichara et al., 2022). Future studies can build on the findings to compare understandings of NOS along a continuum of science expertise, explore the potential role of the FRA-NOS in promoting science identity development of K-16 students, and support science communicators in crafting messaging that further the public's scientific understanding of science.

Empirical studies using FRA, particularly those focused on curriculum policy from different countries such as Ireland (Erduran & Dagher, 2014b), Italy (Caramaschi et al., 2022), and Taiwan (Yeh et al., 2022), have shed light on the underrepresentation of the social and institutional aspects of NOS, namely the financial and political components. This pattern of findings is echoed in studies on textbooks in Australia (e.g., McDonald, 2017), Germany (Reinisch & Fricke, 2022), and Lebanon (BouJaoude et al., 2017; Salem, 2021). However, it was missing from public's discourse as expressed in COVID-19 tweets (Bichara et al., 2022). Since the FRA provides a lens to highlight some of the shortcomings of science curricula and textbooks, it can identify in very concrete terms how revision and reform can ensure that significant social-institutional dimensions of science are brought to the foreground in science education. Indeed, the FRA categories provide a way to organize and orient curriculum developers and textbook writers to be deliberate and purposeful in the inclusion of the social-institutional FRA categories in their resources.

In addition to revising curricula and textbooks to include additional aspects of NOS, there are further implications for teaching and teacher education. How teachers teach NOS is tightly connected to their pedagogical content knowledge (PCK) about NOS, and that knowledge is lacking in adequacy if it is missing or limited in scope. Even in cases where teachers are steeped into some aspects of NOS, their background knowledge of science and NOS has been found to limit their ability to build or guide students' epistemic curiosities (Wahbeh & Abd-El-Khalick, 2014). Thus, further work is needed to integrate FRA-NOS conceptions with teachers' PCK in different science domains. Additional work is needed to support teacher integration of the FRA to NOS ideas into the curriculum by developing educative curriculum materials that are specifically intended to promote teacher learning. When properly designed, these materials enable teachers to "develop more general knowledge that they can apply flexibly in new situations" (Davis & Krajcik, 2005, p. 3). The educative curriculum materials can build questions around historical cases or can centre on contemporary issues accompanied by reflective questions that span multiple FRA categories. A good framework for developing such materials has been developed by Inêz et al. (2021) "Integrative Model for Teaching NOS in Biological Education" (IM-NOSBIO). This model combines the FRA with the Conceptual Framework of Biology and the Pragmatic Conception of Models as Epistemic Artifacts. The authors use IM-NOSBIO to illustrate how history of science is used in the context of the cell theory to teach the nature of science along the various FRA categories. This case exemplifies how rich domain-specific cases can be built around specific science theories to support teacher PCK. Future cases can be developed using this IM-NOSBIO to support teacher learning and application of NOS. Similarly, parallel models informed by other science domains can be developed to facilitate the creation of discipline-specific units that fit well into existing curricula.

Some FRA assessment tools have been developed to explore pre-service teachers' (Kaya et al., 2019) and students' (Çilekrenkli & Kaya, 2022; Petersen et al., 2020) understanding of the nature of science. Future research might consider exploring synergies and tensions between the intended NOS-infused curriculum goals, teacher instruction, and student learning outcomes. BouJaoude and colleagues (2022) suggest that "the FRA provides more opportunities for culturally diverse students and their teachers to discuss issues of power and oppression in science and how these may or may not be addressed" and consequently promote "fundamental aspects of multicultural science education" (BouJaoude et al., 2022, p. 566). Considering that the claim that the FRA's holistic categories possess the "structural potential and flexibility to guide metacognitive reflection within an equity and social justice agenda" (Dagher, 2020, p. 54), additional research is needed to articulate and evaluate specific strategies that use the FRA to support multicultural and justice-oriented science education goals.

5 Conclusion

In this paper, we provided an overview of the FRA-NOS in science education, addressed some questions about it, situated the significance of the FRA in contemporary and pressing science education issues, and proposed several themes for future research. NOS is complex, but the FRA to NOS enables educators to break down that complexity into simpler components, while keeping track of their relational elements. The intention is not to transform teachers or students into philosophers and historians of science through a complex theoretical framework to be presented as such, but rather to support their understanding of sources of scientific knowledge, the nature of evidence that underlie claims, the limits of these claims and their relevance to specific theories and applications and the cultural norms that govern the production and certification among other aspects

As argued in this paper, the FRA-NOS provides science educators, teacher educators, and teachers with multiple tools to address the myth of neutrality in science through exploring its components in contemporary science-society or historical contexts. The FRA is an orientation to science curriculum and instruction that can help situate scientific knowledge in its cognitive, epistemic, and social-institutional context. But its utility is not limited to traditional education settings and has been used in other contexts to ask new questions that are relevant to the formation of future scientists and for science communicators who aim to improve the public understanding of science (e.g., Bichara et al., 2022). Future research is poised to shed additional light on different ways in which the FRA can be deployed effectively to support the attainment of worthwhile educational, scientific, and societal goals.

Declarations

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

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