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SI: NATURE OF SCIENCE

Investigating Coherence About Nature of Science in Science Curriculum Documents

Taiwan as a Case Study

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Abstract
The article focuses on the analysis of curriculum documents from Taiwan to investigate how benchmarks for learning nature of science (NOS) are positioned in different versions of the science curricula. Following a review of different approaches to the conceptualization of NOS and the role of NOS in promoting scientific literacy, an empirical study is reported to illustrate how the science curriculum documents represent different aspects of NOS. The article uses the family resemblance approach (FRA) as the account of NOS and adapts it for analysis of the curriculum documents. The FRA defines NOS as cognitive-epistemic and social-institutional systems that serve as constructs of knowledge categories with a high level of interconnectedness. The FRA was used as an analytical tool for investigating two sets of Taiwanese curriculum guidelines published 10 years apart, providing an opportunity to discuss how NOS is addressed in the curriculum reforms. The findings show a shift away from the excessive centralization of the cognitive-epistemic system to a consideration of the social-institutional system. Modifications to the benchmarks are proposed in order to achieve a more holistic and progressive approach to NOS. The article contributes to studies on NOS in science education by illustrating how the FRA can act as a tool for exploring interconnectedness of NOS ideas in the curriculum.

1 Introduction

Science literacy has been one of the main goals in science education (AAAS, 1993/2009; NGSS Lead States 2013; NRC 1996). Different interpretations of scientific literacy include a

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"broad and functional understanding of science for general education purposes" (DeBoer 2000, p. 594) and "the ability to engage with science-related issues and with the ideas of science as a reflective citizen" (OECD 2017, p. 22). No matter what scientific literacy targets, figuring out "what counts as science" and "what science should be taught" has been the central question for science education (Abd-El-Khalick 2013; Clough 2011; Michel and Neumann 2016; Osborne et al. 2003). A line of research that focuses on such fundamental questions about science is "nature of science" (NOS). Although NOS has been an important topic in science education for decades (Abd-El-Khalick 2012; Abd-El-Khalick and Lederman 2000; Lederman and Lederman 2014; Matthews 2015), the diverse ways in which science can be conceptualized have led to various philosophical stances (e.g., Irzik and Nola 2014).

In a practical sense, science refers to the underlying practices and thinking that dominate scientists' ways of doing research. These rules can be domain-general or domain-specific, since disciplinary features shape scientists' habits of mind and define what "scientific" means, but at the same time can be universally shared across disciplines. There are scientific methods, but what counts as "scientific" or a "method" is not rigidly fixed. Scholars who embrace different theoretical perspectives such as the consensus view (Lederman et al. 2002; McComas 1998), whole science (Allchin 2011), features of science (Matthews 2012), and family resemblance approach (Erduran and Dagher 2014a; Irzik and Nola 2014) among others (e.g., Wong and Hodson 2009, 2010) bring different approaches to NOS instruction. Considering that contemporary science education values the authentic science and constructivist teaching approaches, science curricula need to ensure that students' science learning is meaningful and coherent.

2 Nature of Science in Science Education

Science is usually conceptualized as a body of knowledge, set of methods, or collection of ways of knowing, but it should also be considered as a school of thought that is shared by members of the scientific community, one that dominates how scientists think and act (Kuhn, 1962/1996). Lederman (1992) argued that the core of NOS includes the epistemology of science, science as a way of knowing, or the values and beliefs inherent to the development of scientific knowledge. There is no consensus on further definitions beyond very particular tenets such as tentativeness of scientific knowledge, since different researchers approach characterizing NOS from various perspectives. Nevertheless, developing students' understanding of NOS is still a critical learning objective, as is evident in major international curriculum standard documents (e.g., NGSS Lead States 2013). The identified myths or misunderstandings of NOS held by teachers and students (Kampourakis 2016; Lederman et al. 2002; McComas 1998) offer us a reference point for calibrating the focus of NOS instruction.

It should be noted that scientists' practices are interconnected by nature in order to respond to ever-changing contexts and experimental situations. For example, the NRC (2012) proposed eight specific practices for science and engineering that fall within three spheres (i.e., investigating, evaluating, and developing explanations and solutions). Scientists may begin with observations in the investigation stage but choose calculations when dealing with quantitative data or reasoning the theories behind the phenomena. The selected practices should be rationally coherent regarding the precursor logic and scientific thinking and social-cultural attachment (e.g., representation, discourse, and social certification) (Erduran and Dagher 2014a). Besides the variability of science, the complexity of NOS also comes from the interrelatedness of its themes (Osborne et al. 2003). Historical cases can be useful learning materials because they introduce how scientific thinking and the science process have occurred. Explicit-reflective teaching strategies are greatly used in helping students to better focus on the characteristics of NOS (Abd-El-Khalick 2013; Clough and Olson 2008; Duschl and Grandy 2013; McComas 1998; Niaz 2009). Similar to what Abd-El-Khalick (2012), Erduran and Dagher (2014a), and Irzik and Nola (2014) suggested regarding a blend of domain-general and domain-specific NOS learning, it is important for science educators to unpack the intractably interconnected themes on NOS to help science teachers deal with the inherent homogeneity and heterogeneity of science.

2.1 Interconnectedness and Coherence of NOS Aspects

Given the complexity of NOS, effective curriculum standards and instructional approaches need to be developed for teaching and learning. A list of the features of NOS cannot be exhaustive or complete, but it may offer teachers a quick summary of what science is about. However, such a principle or recipe-like list can easily be taken as norms (or myths) if they are presented without a careful, comprehensive, and detailed interrogation (Abd-El-Khalick et al. 1998; Lederman et al. 2002). Describing the concerns regarding teacher readiness commonly emerging in response to NOS instruction, McComas (2008, 2017) modified the consensus list, using clusters and a three-circle Venn diagram to conceptualize major aspects of NOS instruction (i.e., tools and products of science, science knowledge and its limits, human elements of science). The interconnectedness elements delivered in the diagram are critical features of science and should not be neglected.

A recent depiction of NOS focused on the interconnections of various aspects of NOS is the so-called family resemblance approach (FRA) originally proposed by philosophers of science Irzik and Nola (2014) and extensively developed and adapted by science education researchers Erduran and Dagher (2014a). The idea of "family resemblance" was discussed by Wittgenstein. Irzik and Nola (2014) applied this idea to the consideration of NOS. Family resemblance was used to denote similarities and differences shared among sciences. For example, although observation is common to all science disciplines, the precise nature of observation and what counts as evidence may be fairly unique in different fields of inquiry. Irzik and Nola (2014) suggested categories that researchers might use to group features of sciences. This categorical structure allows for both domain-general and domain-specific elements to be captured. They defined science as "a cognitive system whose investigative activities have a number of aims that it tries to achieve with the help of its methodologies and methodological rules, and when successful, produces a number of outcomes, ultimately, knowledge" (p. 602).

The FRA embraces important features of NOS. For example, science is a "special form of critical inquiry" (Nola and Irzik 2006, p. 203). It tells an inclusive and coherent "meta-story" about how science works, ranging from its aims and values to practices and knowledge as well as the social context. Scientists' aims and values may shape their science activities, determine the methodologies they select, and seek societal applications of their work. The process is not linear but can be iterative, bidirectional, or mutually interconnected. The philosophical idea of family resemblance justifies the similarities as well as the differences among science domains.

From an FRA perspective, science is a cognitive-epistemic system (including aims and values, practices, methods and methodological rules, and scientific knowledge), as well as a social-institutional system (including social ethos, social values, professional activities, social certification and dissemination, social organizations and interactions, financial systems, and political power structures) (Erduran and Dagher 2014a). The FRA provides a comprehensive representation of different aspects that characterize the scientific enterprise. Erduran and Dagher (2014a) argued that weaving a broader set of social-institutional aspects into the cognitive-epistemic aspects of science would likely serve a wider range of learners, especially those who might not be drawn to the cognitive aspects that dominate school science. Categories within this two-level system are interconnected, and it is this coherence that rationalizes or justifies how students' ability to think and act like scientists can be structured.

These categories express 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 interplay between these categories can be visualized in the FRA wheel (see Fig. 1). Erduran and Dagher (2014a) argued that understanding NOS in science education requires an appreciation of a collective and holistic account of science that is captured by these categories. The holistic approach is a core value for teaching and learning NOS from an FRA perspective. The rationale behind teaching NOS in a holistic way is to present science as it operates in the real world. Actual cases and scientific events offer authentic details regarding what science is and how it works. Therefore, students' NOS concepts become evidence-based, case-dependent, and inductively transformed. Teaching NOS via a holistic approach demands that science teachers have proper grasp of what science is and how it works, not only from textbooks or codified principles but also from a sophisticated understanding of the underlying ideas about science (Erduran et al. 2018).

The FRA wheel illustrates important categories in science and advocates the interconnected relationships among categories. The definitions of the particular FRA categories are provided in Table 1.

The following example illustrates how the FRA categories can be useful to depict how science works. The winners of Nobel Prize in Physiology or Medicine 2015 are an authentic case explaining how the categories in the FRA actually interact. This prize was awarded jointly, to be shared 50% by William C. Cambell and Satoshi Omura and 50% by Youyou Tu.

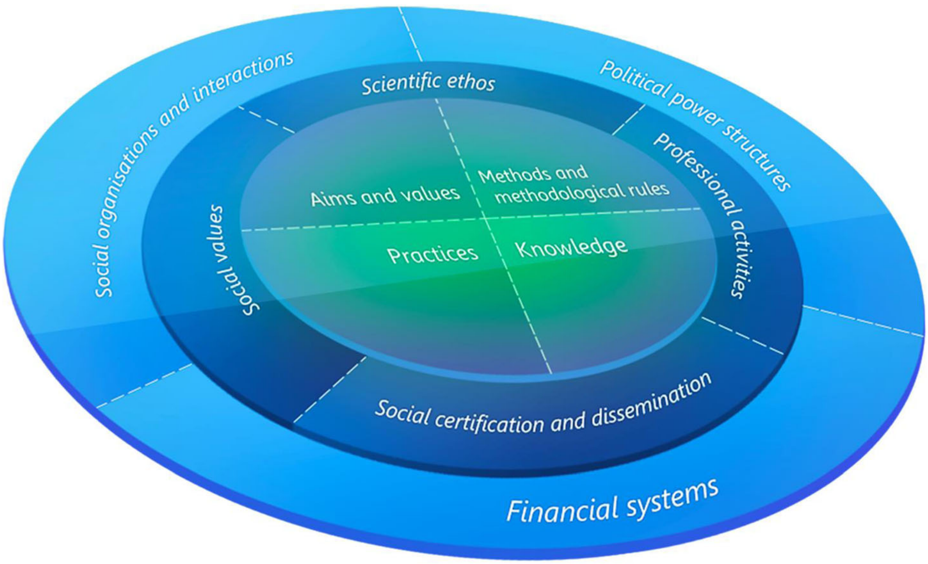

Fig. 1 The FRA wheel (reprinted from Erduran and Dagher, 2014a, p. 28)

Table 1 FRA categories (from Erduran and Dagher 2014a)

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 reasoning.
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 interrelated 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.
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, honesty, 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 imposes its own values and interests. Science is not universal, and 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.

The scientists were honored for their discovery of a novel therapy that effectively cures infectious diseases (i.e., parasite infections, malaria). There are many issues to discuss regarding Youyou Tu's achievements. She began her malaria research after she was recruited to join Mission 523, a national institute searching for a cure for malaria (aims and values, social values). She led her team by reviewing ancient texts for historical methods of fighting the disease, and then narrowed down her search to the effective compound of artemisinin obtained from wormwood.

Initial attempts were not as effective as she expected, so she returned to the ancient texts and continued testing, not only on mice but also on herself, to ensure the medication's security (methods and methodological rules, scientific practices, scientific ethos). Enzyme models were central in this episode along with the lock-and-key and induced-fit theories (scientific knowledge). The medication was found to significantly decrease the death rate from malaria, so she published her findings anonymously in 1977 (social certification and dissemination). Her contribution went unrecognized until she published her autobiography, but she was soon attacked for ignoring the contributions of her colleagues Cambell and Omura who made similar discoveries (professional activities, scientific ethos, social organizations and interactions). Gender issues, Chinese traditional medicine, Westernization, and massive production for financial gain in the era of civil revolution would also be useful topics to discuss (political structures, social values, and financial systems). Youyou Tu's example offers authentic materials for teachers and students to use in conceptualizing how science operates in a broad sense. It also aligns with the high school curriculum in Taiwan, which is the context of curriculum analysis to be reported in the rest of this paper.

2.2 NOS in Curriculum Documents

Curriculum guidelines are used to highlight the ideal curricula for educators to pursue (Goodlad 1979), as well as chart students' expected learning progression in terms of target knowledge maps. Guidelines are often substantially responsible for what learners learn and teachers assess (Sleeter and Carmona 2017), but competence acquisition should not be limited to benchmarks. Therefore, we can see how NOS is conceptualized and expected as learning goals from contemporary curriculum documents. "A Framework for K-12 Science Education" indicates that NOS categories are closely associated with practices (e.g., scientific knowledge is open to revision in light of new evidence) and crosscutting concepts (e.g., science is a human endeavor) (Bybee 2014; NGSS Lead States 2013).

On the other hand, PISA distinguishes epistemic knowledge from content knowledge and procedural knowledge within the construct of scientific knowledge. Epistemic knowledge critically supports students' core competency development, i.e., explaining phenomena scientifically, evaluating and designing scientific enquiry, and interpreting data and evidence scientifically (OECD 2017). Beyond the epistemic and cognitive emphasis, there seems to be a trend of expanding the realm of NOS to encompass social and institutional contexts (NGSS Lead States 2013). Kaya and Erduran (2016) compared curriculum guidelines adopted in Turkey, Ireland, and the USA and found an increasing emphasis on the social-institutional system, in addition to a comprehensive stressing of the cognitive-epistemic system. It is interesting to see how NOS categories (or aspects) are interconnectedly addressed, especially since this also reflects how the world operates.

If it is to be effective, a curriculum must be coherently planned and designed. Curricular coherence indicates "sensible connections and co-ordination between the topics that students study in each subject within a grade and as they advance though the grades" (Newmann et al. 2001, p. 298). Abd-El-Khalick (2012) selected four major aspects of NOS (i.e., tentative, theory-laden, empirical, and social aspects of NOS) and used increasing levels of specificity, complexity, and problematization to propose what should be learned along the learning progression from elementary school to teacher education. Allchin (2011) used the concept of "Whole Science" to communicate how students' understanding of science was authentically based on how scientific claims and practices that are contextually formed. Hence, NOS curriculum documents not only can potentially reveal what students can be expected to learn about NOS, but they can also be held up to scrutiny helping students engage in meaningful learning.

2.3 Research Questions

Major educational reforms are being advanced in Taiwan, and a new curriculum is being launched in 2019. NOS is one of the few foci in the Taiwanese science curriculum that have survived since the old curriculum documents. Therefore, it is important to examine the present level of alignment between benchmarks and educational research evidence, as well as determine what improvements can be made to the existing guidelines. This process will allow for an efficient but comprehensive means of examining what current science curricula highlight and what they might still lack in terms of significant goals related to scientific literacy. The findings of this research will offer educators the opportunity to unpack the existing benchmarks in order to understand what they emphasize and what needs to be further reinforced. Researchers who are interested in unpacking curriculum guidelines and seeking instructional directions for holistic NOS understanding can use the FRA as an analytical tool just as this study has done. Our interest thus rests on the coverage of NOS in the science curricula in Taiwan. Hence, we pose the following key questions:

- How is NOS represented in the two curriculum documents in Taiwan?
- Are aspects of NOS represented in an interconnected fashion in these curriculum documents and if so how?

3 Method

In order to answer our research questions, several curriculum documents from Taiwan were compiled and analyzed. The sources of the data were the "Grades 1-9 Science and Technology Curriculum Guidelines" (MOE 2006) and the "Grades 1-12 Science Curriculum Guidelines" (NAER 2016) used in secondary schools in Taiwan. Each document was written to inform the stakeholders including teachers and teacher educators. The documents share a comprehensive educational goal which is "to increase the national level of science literacy" (MOE 2006, p. 5). However, each document approaches this goal differently, as reflected by the benchmarks and curriculum content specified. A brief introduction to the two documents is given in Table 2. Due to the research focus of this study, only those benchmarks belonging to "attitudes toward science and NOS" were analyzed.

The benchmarks for the NOS aspects of the two curriculum documents (see Table 3) were examined to see how NOS is conceptualized and transformed in terms of science curriculum development in Taiwan. The FRA wheel reviewed in Fig. 1 has previously been applied to curriculum evaluations in other national contexts (e.g., Erduran and Dagher 2014b; Kaya and Erduran 2016). Category definitions from Table 1 were used as references when the benchmarks were coded. Multiple codes were possible for each

Table 2 Background information on two curriculum documents from Taiwan

	Grades 1-9 Science and Technology Curriculum Guidelines (MOE, 2006)	Grades 1-12 Science Curriculum Guidelines (NAER 2016)
Target groups	4 groups: grades 1–2, 3–4, 5–6, and 7–9	5 groups: grades 3–4, 5–6, 7–9, 10–12 (communal), and 10–12 (advanced)
Goals	To increase students' science literacy	
Focus domains	1. Science process skills 2. The development of science and technology knowledge 3. The nature of science 4. The advancement of technology 5. The development of scientific attitudes 6. The development of processing intelligence 7. Scientific applications 8. Design and making	1. Inquiry ability - Thinking ability - Problem solving 2. Attitude toward science and nature of science

benchmark, if more than one FRA category was applicable. In other words, a curriculum benchmark could count both as instances of scientific practices and scientific knowledge if the statement made reference to both aspects. The coding was conducted independently by two researchers, and any disagreements were resolved through discussion. To measure the interrater reliability, Cohen's kappa coefficient (Cohen 1960) was used, since it showed the extent to which the observed agreement between the two raters was superior to the random agreement probability. Each benchmark was examined by the 11 FRA codes. The kappa coefficient was calculated based on a single true-false coding method. The initial interrater agreement was $K = .76$ for the 30 benchmarks, which was considered as sufficient. Eventually, full agreement for each benchmark was reached.

Taking III-3 as an example (i.e., "Believe that all people can be scientists, no matter their gender, backgrounds or races"), this benchmark was coded as "political power structures" instead of "social values," given the definition of this category that appears in Erduran and Dagher's (2014a) book. By definition, this category is inclusive of aspects of politics and culture such as race, gender, and colonialism, which have played a role in the shaping of the scientific enterprise throughout the history of science. In contrast, the category of "social values" includes values such as honesty and skepticism that characterize how scientists approach or should approach their work. Hence, our characterization was informed by the emphasis of the published and theoretical definitions of the categories. Even though the reference to gender in the statement was fairly neutral, the category itself presupposed a history of gender discrimination in scientific professions.

Holistic aspects of NOS were examined in two ways. First, the 8 principles of curriculum development (Oliva and Gordon 2013) were used to analyze the structural quality of the two versions of the guidelines. The comparison results illustrate a comprehensive picture of how the curricula developed and summative indications of what needs to be improved. Second, the benchmarks were unpacked to examine what had and had not been emphasized in terms of FRA elements (see Fig. 1). The comparison of the guidelines also informed researchers regarding how the reforms evolved across time.

Table 3 NOS-focused benchmarks in science curriculum documents from Taiwan

	9-year compulsory education (MOE, 2006)	12-year compulsory education (NAER 2016)
Grades 1–2	1-1 Learn how to describe what has been observed.	
	1-2 Know that, with careful observation, one can often come up with new discoveries.	
Grades 3–4	2-1 Verifications and tests can be adapted and applied to confirm ideas.	II-1 Know that scientific exploration begins with questions.
	2-2 Know that identical experimental conditions should produce similar results.	II-2 Know that scientists use different methods to explore patterns in the natural and material worlds.
	2-3 Believe that changes in a phenomenon are the results of particular factor changes.	II-3 Know that innovation and imagination are important elements in science.
Grades 5–6	3-1 Through scientific investigations, comprehend that scientific knowledge is built upon the foundation of tests.	III-1 Through scientific investigations, understand that scientific knowledge is built upon authentic experience and evidence.
	3-2 Know that evidence for certain events is difficult to establish (e.g., UFO sightings) and thus are not subject to scientific tests.	III-2 Know that scientific claims and conclusions change in the presence of new evidences.
	3-3 Arrive at the conclusion that anticipation can be made and certain events can be verified on the basis of scientific knowledge.	III-3 (Believe that) All people can be scientists, no matter their gender, backgrounds or races.
	3-4 Know that often problems can be found out either through reviewing the same data from a new perspective, or through examining the same theories relative to new data.	
	3-5 Know that different results may occur under identical experimental conditions due to factors that are yet to be controlled.	
Grades 7–9	4-1 Make sense of the fact that science is knowledge built upon investigation and verification.	IV-1 Know that the appropriateness of scientific observations, measurements, and methods is determined by socially constructed standards.
	4-2 Be able to tell the difference between observations and scientific theories.	IV-2 Be able to understand the correctness and consistency of scientific knowledge vary by the contexts of the scientific research.
	4-3 Know that certain theories are not logically related and sometimes they do not agree with each other, which is a sign of incompleteness. Valid theories are bodies of knowledge built upon tests; they should convey a sense of logic without disagreeing with one another.	IV-3 Know that scientists are determined, prudent, and logical thinkers with curiosity, imagination, and a hunger for knowledge.
	4-4 Know that science is a prudent process of study but it can be redefined by new discoveries or observations on the basis of new perspectives.	
	4-5 Know that verification can be established on the basis of scientific theories.	
	4-6 Believe that the universe changes and evolves in a regular pattern.	

Table 3 (continued)

	9-year compulsory education (MOE, 2006)	12-year compulsory education (NAER 2016)
	4-7 Know that explorative scientific activities do not necessarily require a fixed approach. However, they usually include the following: collection of evidence, logical inference, establishing a hypothesis through imaginative thinking, and data interpretation. 4-8 Learn how to make data entries accurately and precisely; be open-minded and realize that tests and experiments should be repeated for verification. All these are the foundations of reliable scientific knowledge.	
Grades 10–12		Vc-1 Understand that scientific inquiry refers to various methods, tools, and techniques for encountering evidence collected from different areas; it is then used to support certain explanations, in order to strengthen the effectiveness of scientific claims. Vc-2 Understand that scientific ways of thinking are empirically based and logically defined to withstand repetitive investigation and speculation. Vc-3 Learn that science can be useful in improving human life, but it does not solve all human problems; know that the development of technology may also cause environmental or ethical issues.

4 Results

Assuming that it is more meaningful to teach NOS in a coherent manner where different aspects are interrelated, the focus should be on the quality of the curriculum statement (e.g., its depth, component variety, interconnectedness) rather than on pursuing an exhaustive list of all possible benchmarks. The observations, as shown below, were based on how NOS is conceptualized in curriculum documents. Any identified gaps reveal directions for science educators to remedy through teaching practices. The assumption for the value of the holistic NOS is based on substantial research in classroom-based research that students find it difficult to make sense of particular issues, concepts, principles, and so on in isolation (e.g., Bransford et al. 2000). Moreover, students find it difficult to transfer their knowledge to new problems and contexts because their understanding is fragmented and disconnected (e.g., Schunk 2004). The analysis of the curriculum documents from Taiwan led to several themes.

4.1 Cognitive-Epistemic System as the Core of an Increasing Engagement with the Socio-institutional System

The NOS benchmark guidelines mainly emphasized the cognitive-epistemic system (MOE 2006); the social and institutional contexts emerged in the latter guidelines (NAER 2016). Tables 4 and 5 present the code combinations and frequencies of the old and new guidelines. The dots in the tables indicate the presence of at least one instance of the FRA category. If

Table 4 Coding results of the curriculum documents for grades 1 to 9 (MOE, 2006)

	Cognitive-epistemic system				Social and Institutional Contexts
Benchmark Codes	Aims and Values	Methods	Scientific Practices	Scientific Knowledge	Scientific Ethos
1-1			•		
1-2	•		•		
2-1	•	•	•		
2-2		•	•		
2-3		•	•		
3-1	•	•		•	
3-2		•			
3-3		•		•	
3-4			•		
3-5			•		
4-1			•	•	•
4-2			•	•	
4-3		•		•	
4-4	•	•	•		
4-5		•		•	
4-6	•				
4-7		•	•		
4-8	•	•	•	•	
Total	6	11	12	7	1

The two-digit numbers (a-b) indicate the following: "a" indicates grade levels (1 means grades 1–2, 2 means grades 3–4, 3 means grades 5–6, 4 means grades 7–9) and "b" indicates serial numbers of guidelines within those grade levels.

Table 5 Coding results of the curriculum documents for grades 1 to 12 (NAER 2016)

Benchmark	Cognitive-epistemic system				Social and Institutional Contexts			
Codes	Aims and Values	Methods	Scientific Practices	Scientific Knowledge	Social certification & dis-semination	Scientific Ethos	Social values	Political power structures
II-1		•						
II-2		•	•					
II-3	•							
III-1	•	•	•	•				
III-2	•		•					
III-3								•
IV-1		•	•		•			
IV-2	•	•		•				
IV-3	•					•		
Vc-1	•	•	•					
Vc-2	•	•				•		
Vc-3	•						•	
Total	8	7	5	2	1	2	1	1

The benchmark codes "a-b" indicate the following: "a" indicates grade levels (II means grades 3–4, III means grades 5–6, IV means grades 7–9, Vc means grades 10–12), and "b" indicates serial numbers of guidelines within those grade levels.

there were explicit links between the categories where more than one FRA category was referenced, then a line was used to represent that the categories were linked. A total of 36 of the 37 codes (97.30%) from the old benchmarks fell within the cognitive-epistemic system category, in contrast to the 22 out of 27 codes (81.48%) from the new benchmarks. Scientific practices and methods were the top two focus areas in the earlier version, since they were indicated in 12 and 11 out of 18 benchmarks, respectively. Aims and values became the category with the highest consideration (8 out of 12), following up with methods (7 out of 12) and scientific practices (5 out of 12). Scientific knowledge was less emphasized in new benchmarks (16.67%), in contrast to the old ones (39.89%) (NAER 2016).

Some of the NOS focus shifted to the social-institutional system. The inclusion of social and institutional contexts began at grade 7 in the earlier document (MOE 2006), but in grade 5 in the more recent one (NAER 2016). Scientific ethos was persistently pursued throughout both documents. Characteristics of professional scientists such as logical thought, patience in investigations, and a speculative attitude were all emphasized. However, the ethics of science is also worthy of instruction, such as with the legality of certain acts and respect for issues faced by the subjects of experiments and research colleagues. The new guidelines began to develop students' conceptualization of science as a communal product determined by socially constructed norms and efforts to improve society, conducted without bias toward researchers' backgrounds.

4.2 Interconnectedness Among Methods, Scientific Practices, and Aims and Values

Erduran and Dagher (2014a) have argued that NOS will be more meaningful for learners if they consider it in a holistic fashion. The interconnectedness of the FRA categories was based

Table 6 Comparison of the two curriculum documents from Taiwan

	Grades 1–9 (MOE, 2006)	Grades 1–12 (NAER 2016)
Scope	Cognitive-epistemic: aims and values, methods, scientific practices, scientific knowledge Social-institutional: scientific ethos	Cognitive-epistemic: aims and values, methods, scientific practices, scientific knowledge Social-institutional: social certification and dissemination, scientific ethos, social values, political power structure
Relevance	Scientific inquiry, epistemology of science	Scientific inquiry, scientific ways of thinking, scientific enterprise
Balance	5 elements out of 11, mainly on cognitive-epistemic system	8 elements out of 11, spreading to social-institutional contexts
Integration	Target competences unpacked in discrete pieces	Target competences in an inclusive way
Sequence	From operational experiences to scientific knowledge elaboration	From explorative to scientific ways of thinking
Continuity	Comprehensively by levels	Individually by 3 major strands
Articulation	Benchmarks are elaborated and newly added by grades	Benchmarks are consistent and engage more flexibility of science
Transferability	Centered around scientific practices within the science context	More socially embedded context is added

on this assumption. In response to such a supposition, curriculum benchmarks should not only encompass a variety of FRA components but also further elaborate upon them with a higher level of coherence. If we calculated the number of FRA codes that benchmarks in the two curriculum guidelines encompassed, the average number of codes for each benchmark was similar: 2.05 FRA elements per benchmark in the earlier document while 2.25 elements in the latter. High-frequency code combinations in each benchmark in both versions included (a) methods and scientific practices (10 benchmarks), (b) aims and values and methods (8 benchmarks), and (c) aims and values and scientific practices (7 benchmarks) as well as methods and scientific knowledge (7 benchmarks). Among these combinations, almost all the benchmarks that encompassed scientific knowledge were found coming up with methods (7 out of 9 benchmarks).

The most frequent combination in the benchmarks (methods and scientific practices) across the two versions reflects a distinctive element of science in nature: that it is inquiry-related. This combination was introduced to students beginning in the third and fourth grades, was absent in grades 5 and 6, and then was readdressed with expanding connections at the middle-school level (MOE 2006). Benchmarks in the third and fourth grades expected students to demonstrate a principle-like understanding mainly around experiment- making and inquiry (e.g., verifications and tests, variable controls) (see benchmarks 2-1, 2-2, 2-3 in Table 3), while the flexibility of the methods and practices of science was not introduced until grades 7 to 9 (4-4, 4-7, 4-9). As for the new benchmarks (NAER 2016), the combination of methods and scientific practices was consistently introduced throughout each grade level in a progressive scheme (NAER 2016). Expectations for the three-to-four and five-to-six grade levels focus on how inquiry is naturally formed (e.g., pattern exploration in nature, investigations of experiences and evidence) (see II-2, III-1 in Table 3). The aforementioned flexibility of scientific methods and practices was retained at the elder levels but added the idea of socially constructed standards (see IV-1 in Table 3); however, the focus shifted to ways of making science robust and effective through methods and practices (see Vc-1 in Table 3).

4.3 Comprehensive Check of Guideline Quality

A comprehensive depiction of how these two guidelines differed and evolved can be found in Table 6. First, old guidelines had a narrower NOS scope that primarily centered around the cognitive-epistemic system. The old guidelines also placed extensive emphasis on the development of students' knowledge of and about inquiry experimentation (e.g., 2-1, 3-1, 3-4 in Table 3); in the new guidelines, this shifted to inquiry (i.e., II-2, III-2, IV-2, Vc-2 in Table 3) and scientific ways of thinking (i.e., II-2, III-2, IV-2, Vc-2 in Table 3). In contrast to a discrete list of inquiry skills and scientific methods, the new guidelines had three benchmarks for each grade level; each was aligned with the increasing level of difficulty involved. Second, the new benchmarks also had a more balanced array of NOS focuses. Although there were only three for each grade level, these benchmarks were written both concisely and inclusively. For example, the old benchmarks were more principle-like, indicating rules of science (e.g., 3-2, 3-5, 4-3 in Table 3), but the new items offered more flexibility, if also some potential ambiguity (e.g., III-2, IV-1 in Table 3).

Third, both curriculum documents were indeed planned spirally (Bruner 1960; Harden 1999). The structural quality improved greatly from the old to the new guidelines, since the old benchmarks that shared high relevance and similar levels of cognitive difficulty were clustered at the same grade levels. For example, there were five benchmarks—mainly for inquiry—listed for fifth and sixth graders, while there were only two to three benchmarks for younger students. These benchmarks were not matched in vertical progression nor systematic in terms of horizontal scope; therefore, learning gaps may take place, just like the aforementioned most-frequent combination missing at grades 5 to 6. By comparison, the new guidelines granted more flexibility to teachers to design and implement science instruction.

5 Discussion

Understanding "what is science" has been an important curricular goal for several decades (Duschl and Grandy 2013). For the sake of curriculum development, another fundamental question that must be considered is "why science." Allchin (2017) further argued that scientific literacy as a functional literacy would empower citizens to scientifically judge claims and make decisions. Therefore, each scientific event that offers rich and authentic information for use in education and discussion should not be limited to scientific knowledge but instead extend to the scientific enterprise and scientists, as well (Allchin 2012; Cooley and Klopfer 1963). Yet there have also been questions regarding the credibility of science and the argument that science functions like an authoritative epistemic enterprise. Socially determined norms and the ambiguous boundary between science and social science make people speculate the value of science learning (Gieryn 1999). Considering that we are not pursuing *the* science, the FRA framework offers us a good structure to reorganize our understanding of science (e.g., domain-general and domain-specific, cognitive-epistemic, and social-institutional). Learning how scientific endeavors are coherently weaved under certain contexts or conditions shall deepen teachers' and students' understanding of science.

A follow-up concern in NOS education is not what science we should target, but rather the coherence and interconnectedness of science that functions like a comprehensive, meta-level science conceptualization. Similar to the idea of why the explicit-reflective approach is a favored teaching strategy in NOS instruction (Abd-El-Khalick and Akerson 2009), the FRA framework offers a categorical structure for teachers and students to use in unpacking what they observed and investigating what may exist beyond. The goal of obtaining a holistic understanding is not limited to science; different schools of thought (e.g., social science, religion) may share a similar structure though with some differences. This is another application of family resemblance. Now that metacognitive training has been found to facilitate teachers' and students' NOS understanding (Abd-El-Khalick and Akerson 2009), NOS education that emphasizes a holistic view should also loop back to students' metacognitive thinking in different fields.

The value of coherence goes beyond phenomenon-based features like dynamic and interlocking relationships among categories; what's more, scientists rely on their decisions regarding what methods to employ and how results should be analyzed and justified (Lederman et al. 2002; Irzik and Nola 2014). Erduran and her colleagues (Erduran and Dagher 2014a; Erduran and Kaya 2018) proposed a benzene ring heuristic (BRH) to illustrate how scientific practices relate, avoiding a linear order (i.e., the outer hexagonal ring). Socio-cognitive processes like reasoning and social certification underscore the epistemic components (i.e., the internal ring). Another example is the Theory Law Model (TLM), which emphasizes how different forms of scientific knowledge (i.e., theories, laws, and models) develop (e.g., growth, extension, revision) and work together to constitute a scientific understanding that explains the natural and physical phenomena within and across disciplines. Yet science teachers may not dedicate time to comprehensively address how these principles of scientific knowledge are related, interact with one another, or evolve.

Such coherence exists not just within but also across categories. We found that aims and values were substantially added to the new guidelines and were connected to other categories. Such a change would help students make better sense of how scientists' practices are shaped by their aims and values (e.g., being objective, empirical adequacy, addressing human needs), which in turn would serve as goal-setting initiation and quality alignment. Abd-El-Khalick (2012) also pointed out that the consensual list is "nuanced, sophisticate [d], and interrelated" (p. 366), so students would benefit from the provision of opportunities to "construct, re-construct, and consolidate their own internally consistent framework" (p. 360). Paying attention to coherence is no less important than learning "what science is," since it sustains the "metacognitive reflection" (Dagher and Erduran 2017, p. 48) believed to be fundamental to the advancement of science. There is now empirical evidence on how FRA-based heuristics can be adapted for use in pre-service science teacher education (e.g., Erduran and Kaya 2018; Kaya et al. 2019).

The two categories most frequently considered among the benchmarks are methods and scientific practices; their connections to other categories were also found to be popular. Such findings echo the use of "inquiry ability" as a main focus of the Taiwanese science curriculum, while "attitude toward science and nature of science" was closer to accommodating inquiry, though both were claimed as foci (see Table 2). The substantial coverage of inquiry-related benchmarks for NOS implies an unclear boundary between inquiry and NOS among science educators (Hodson 2014; Lederman 2006; Ryder 2009). In fact, it is also important to learn inquiry epistemically, in addition to what practices or procedures to follow. For example, conflicts of interest have become universal among stakeholders in the healthcare system (e.g., patients, doctors, medical researchers, pharmaceutical companies); consequently, experimental design and data analysis may be purposefully manipulated while ethics and norms are reshaped to ensure the quality of related medical research, modernizing it such that it meets contemporary needs. Scientists' decisions and scientific results can be greatly influenced by

Table 7 Proposed modifications to the science curriculum documents in Taiwan (NAER 2016)

	Scientific inquiry	Scientific argumentation and modeling	Scientific enterprise	FRA categories
Grades 3–4	II-1 Know that scientific exploration begins with questions *and is for social value.*	II-2 Know that scientists use different methods to explore patterns in the natural and material world; *from this, knowledge of the world is constructed.*	II-3 Know that innovation and imagination are important elements in science, *and that innovative ideas can be elaborated upon to apply to daily-life products and transdisciplinary fields.*	1, 2, 3, 4, 8, 10
Grades 5–6	III-1 Through scientific investigations, understand that scientific knowledge is built upon authentic experience and evidence.	III-2 *Know that scientists make claims and conclusions based on evidence, but these knowledge construction processes are subject to the presence of new evidence and scientists' disinterestedness.*	III-3 Believe that all people can be scientists, no matter their gender, background, or race; *understand that scientists need to participate in different professional activities, take certain roles, and assume certain responsibilities.*	1, 2. 3, 4, 5, 7, 8, 9, 11
Grades 7–9	IV-1 Know that the appropriateness of scientific observations, measurements, and methods is determined by socially constructed standards.	IV-2 Be able to *justify selected practices based on research purposes* and understand that the correctness and sustainability of scientific knowledge vary based on the context of the scientific research.	IV-3 Know that scientists are determined, prudent, and logical thinkers with curiosity, imagination, and a hunger for knowledge; *in addition, scientists may interact with stakeholders to facilitate industries.*	1, 2, 3, 4, 5, 6, 8, 9, 10, 11
Grades 10–-12	Vc-1 Understand that scientific inquiry refers to various methods, tools, and techniques for encountering evidence collected from different areas; it is then used to support certain explanations, in order to strengthen the effectiveness of scientific claims.	Vc-2 Understand that scientific ways of thinking are empirically based and logically defined to withstand repetitive investigation and speculation; *endeavor to construct ideas regarding laws, models, and theories based on explanatory robustness.*	Vc-3 Learn that science can be useful in improving human life, but it does not solve all human problems; know that the development of technology may also cause environmental or ethical issues; *understand scientists have responsibilities to protect human rights and societies' safety.*	1, 2, 3, 4, 5, 6, 7, 8, 10, 11

1, aims and values: 2, methods; 3, scientific practices; 4, scientific knowledge; 5, social ethos; 6, social certification and dissemination; 7, professional activities; 8 social values; 9, political structures; 10, financial systems; 11, social organizations and interactions social and institutional factors. Therefore, ensuring that these belong to "attitudes toward science and NOS" is important, since engaging students in enquiring how science operates and why that is so would facilitate not only students' attitudes toward science but also their command of inquiry.

From a macroscopic point of view, new curriculum documents are better viewed in terms of the alignment of three strands of benchmarks. To best conceptualize how socio-institutional categories naturally co-exist with cognitive-epistemic categories, we proposed modifications to the guidelines with the intention of embedding a holistic, interconnected, and progressive view of the FRA categories, as shown in Table 7. It is important to note that the renaming and modifications are not fundamental changes, since we sought to ensure that the original benchmark objectives were retained, while at the same time making attainable a broad, meaningful coherence with other categories. The phrases in italics have either been modified or newly added. For convenience, we named these strands based on the themes the across-grade benchmarks shared: scientific inquiry, scientific argumentation and modeling, and scientific enterprises. Each has its own theoretical basis; all three mutually support one another and together comprise a more expansive idea of inquiry abilities (i.e., the other foci). The first two strands' names came from the rationale of the NRC's (2012) framework for scientific and engineering practices (Osborne 2011, 2014). However, it should be noted that Lederman (2007) reminded educators not to conflate NOS with scientific inquiry. A more balanced and inclusive scope is needed, especially when NOS discusses the epistemic understanding of science.

After reshaping, the three strands also reflect important aspects of contemporary science education. Besides progressive complexity, the benchmarks at the same grade levels cover as many FRA categories as possible. First, the strand of inquiry begins with understanding why we need inquiry (II-1), how quality inquiry is accomplished (III-1 and IV-1), and how inquiry can be practically implemented and expanded (V-1). Second, "scientific argumentation and modelling" discusses the ways scientific knowledge is constructed, beginning with the view that science is the knowledge upon which we base our understanding of the world (II-2), moving to its tentative nature (III-2) as justified by the research quality that supports it (IV-2), and eventually elaborating to theory-law-model (Vc-2). Finally, the strand of "enterprise" encourages students to appreciate the values of science (II-3) and know the responsibilities of scientists (III-3), expectations for good scientists (IV-3), conflicts scientists may encounter, and limitations of science of which we should be aware (Vc-3). Overall, students' NOS learning, as embedded in these three strands, deepens as the grade level increases. The comparatively longer statements may not be intuitive or easy to memorize for teachers or students; however, the variety and flexibility of science that we expect them to learn should still be purposefully embedded in the curriculum documents. Therefore, for science teachers who are used to unpacking NOS merely via the epistemic-cognitive approach or who are directly told what to teach, the new benchmarks—intentionally filled with referential ambiguity with regard to NOS—may make professional workshops a necessity.

6 Concluding Remarks

To develop students' scientific literacy as an ultimate goal, we are arguing that a holistic understanding of NOS is necessary not only for its value for enabling reflection on how science operates in the real world but also because of its interconnectedness that enables students to understand why and how science works. Rather than discussing what science is by explicating its characteristics, this study attempts to approach NOS through a categorical understanding, but urges that an emphasis be placed on coherence among its categories. The idea of family resemblance is strategically used to interrogate the cohesion among heterogeneity that comes from domain specificity but on the basis of homogeneity that is generally shared. We chose the FRA as the analytical tool, since we think scientists' intentions, activities, and contexts are all interdependent and must be coherently linked, within or across categories. The FRA is a good strategy for teachers and students to organize what have been learned through reconceptualizing how science operates. In summary, the present article makes a contribution to studies on NOS in science education by illustrating how the FRA can act as a tool for exploring interconnectedness of NOS ideas in the curriculum. The FRA in this sense is not only used in a unique methodological manner but the outcome of the use of FRA as an analytical tool offers concrete recommendations for curriculum revision. Ultimately the quality of science curricula will improve when a balanced, comprehensive, and meaningfully interconnected account of NOS can be targeted as learning outcomes.

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