Chapter 10
Teaching Nature of Science Through a Critical Thinking Approach

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10.1 Introduction

In this volume, McComas suggests a number of nature of science (NOS)-related ideas called *subdomains* for the inclusion of NOS in school science. Previously he (e.g., McComas 1998, 2004) and others (e.g., Lederman 2004; Osborne et al. 2003) have developed groups of NOS-related ideas that should be the focus of instruction in K-12 science classrooms. These NOS-related ideas constitute the substantive content of NOS to be taught to students and have received positive reviews by many science educators (e.g., Akerson et al. 2000; Akerson et al. 2011; Khishfe 2008; Khishfe and Abd-El-Khalick 2002; Kim and Irving 2010; Paraskevopoulou and Koliopoulos 2011; Yacoubian and BouJaoude 2010). These and other educators have developed studies in which they have used similar NOS-related ideas and have aimed at guiding students to develop their NOS understandings through engaging them in explicit and reflective discussions on NOS.

In my opinion, *critical thinking* (CT) needs to be a foundational pillar of NOS in school science (Yacoubian 2015). In this chapter, I discuss why and how NOS should be taught *critically* at schools. In taking such a position, I do not underestimate the value of explicit and reflective discussions. As referenced earlier, such discussions have been found to be quite effective. In the paragraphs that follow, I propose CT as a framework for addressing NOS in school science. Such a proposal does not contradict with the method of explicit reflective discussions. In fact, it provides a direction for those discussions.

There are a number of reasons for addressing NOS in school science. Among these reasons are humanizing of the sciences and situating them in personal, ethical, cultural, and political contexts and promoting critical thinking (Matthews 1994).

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These are in addition to enhancing decision making (McComas 1998), particularly on socioscientific issues (Kolstø 2001a; Zeidler et al. 2002), which are controversial social issues related to science with no clear-cut solutions (Sadler 2011). CT is "reasonable reflective thinking focused on deciding what to believe or do" (Ennis 2018a, p. 166). It includes a set of knowledge (e.g., concepts), abilities, and dispositions (Ennis 1996a, b, 2018a; Hitchcock 2018). It is considered an important aspect of scientific literacy (Gunn et al. 2007).

10.2 NOS and Critical Thinking (CT)

There are a number of good reasons for why students need to develop their NOS understandings critically. ***First, CT is a "fundamental educational ideal" (Siegel 1988, p. 2) and almost no one would disagree that it has an important role in the science curriculum.*** There is no reason for why it should not also have a foundational presence in the teaching and learning of NOS (of course, assuming here that one understands the importance of NOS in school science to start with). Siegel explores four main considerations to justify CT as an educational ideal: (1) a moral obligation to respect students as persons, (2) preparation of students for the successful management of adult life, (3) the need of initiation into the rational traditions, and (4) preparing democratic citizens.

Second, CT as a framework for addressing NOS in school science has the potential to help students make good decisions about what views of NOS to adopt. CT is fundamental to decision making (Ennis 1989, 1996a; Lipman 2003; Siegel 1988) and future citizens need to be guided to practice making decisions in the context of NOS. Engaging students in explicit and reflective discussions on NOS-related ideas facilitates in-depth exploration of those ideas to some degree. However, when students start exploring those ideas at depth, they will at some point face divergent and competing positions and thus will need to make decisions regarding those positions—mimicking the skills used by professionals involved in philosophical debates.

One might argue that at the precollege level students rarely engage in decision making on NOS views. After all the aim of K-12 science education is not to prepare philosophers of science. I agree. However, I also approach this issue from a different angle and believe decision making on NOS views can be and should be done in developmentally appropriate ways that progresses as one moves from elementary to secondary and then to the college level. Almost everything taught at schools can be and should be situated across a learning trajectory that provides experiences conducive to their in-depth exploration. Otherwise, learning becomes no more than memorizing facts. Learning NOS should not be an exception to this.

Accordingly, the NOS-related ideas proposed by McComas need to be treated as broad ideas that can have the potential to engage students in some in-depth explorations about them. Abd-El-Khalick (2012a) has suggested that it is important to keep the focus on NOS-related ideas while ensuring that these ideas are "addressed at increasing levels of depth as students move along the educational ladder from elementary school to college-level science teacher education programs" (p. 1047). The NOS-related ideas need to have curricular scope and sequence that get addressed in developmentally appropriate ways and in more depth at every level—whether at the elementary, middle, secondary, or the college level; otherwise, we might risk falling into the trap of treating them as no more than definitions. The latter would encourage rote memorization where students might be at risk of repeatedly learning the same ideas instead of digging deeper into them across a well-defined learning trajectory.

In case of NOS learning, going in depth would also involve making decisions regarding NOS views. This is because of the contested nature of the content that NOS entails. Engaging students in NOS learning at increasing levels of depth would eventually involve having them explore controversies and take critical stance—or at least having them *practice* to do so in developmentally appropriate ways as far as school science is concerned. Consequently, students would need to develop a *critical mindset* as they develop their NOS understandings.

It might look like some of the NOS-related ideas proposed by McComas are easier to teach than others, yet challenges arise as one enters into the details. To elaborate, consider the NOS-related idea that *science is tentative, durable, and self-correcting*. An in-depth exploration, as illustrated in the section that follows, would entail, at some stage across the learning trajectory, students wondering and raising questions as what is tentativeness? How is science tentative? How can scientific knowledge be tentative yet at the same time durable? At a more advanced stage they may need to start exploring different views on tentativeness in science and would also start thinking about, say, whether to adopt a realist or an instrumentalist position for tentativeness in science. The intention here is not to enter into discussions on what students can and cannot do at every developmental level, as that would be an empirical question to pursue. The point that I am trying to make is that students would need to engage in CT to adopt certain positions as they explore those and similar questions. Consequently, throughout their NOS learning pathway, students need to develop a critical mindset, even if as novices they will not make full-fledged decisions on NOS views or adopt positions. A critical mindset would enable them to start developing some CT-related abilities and dispositions, within the context of NOS, so that they can more reasonably explore and appreciate those controversies at more advanced stages in their learning.

Consequently, CT as a framework for addressing NOS in school science has the potential to foster the development of learning experiences not only for an in-depth exploration of NOS but also for decision-making.

Third, CT as a framework for addressing NOS in school science provides the possibility of a developmental pathway for NOS learning using CT as a progression unit. The lack of a developmental pathway for NOS learning has been acknowledged by a few researchers (e.g., Abd-El-Khalick 2012a). Creating a pedagogical sequence for NOS in K-12 science education has been quite a challenge. Many science educators have targeted the same NOS-related ideas across different grade levels and teacher education programs. Combinations of similar NOS-related ideas are used to teach middle school students (e.g., Yacoubian and BouJaoude 2010), secondary students (Bell et al. 2003), preservice science teachers (Schwartz et al. 2004), and in-service science teachers (Akerson and Hanuscin 2007).

Arguably, one reason for the lack of studies that situate NOS instruction in an increasing level of depth can be related to the difficulty in determining what could count as "complex" and "specific" NOS understandings to use Abd-El-Khalick's (2012a) words. It would be hard to come to an agreement as to which philosophical view or views of NOS would be considered the desired "complex" and "specific" NOS understandings, unless a decision is made to move the spotlight away from the substantive content of NOS and focus on the CT process. CT as a foundational pillar of NOS in school science would necessitate developing a developmental pathway for school NOS using CT as a progression unit. One might think about a developmental pathway for NOS learning in terms of a student's engaging in CT about NOS. This seems a plausible path to take especially that there is already some evidence on the developmental nature of CT (e.g., Duschl et al. 2007; Keating 1988; King and Kitchener 1994; Kuhn 1999; Nicoll 1996).

Fourth, pedagogically speaking, the CT literature can provide resources to guide students as they explore NOS. CT has certain attributes the understandings and use of which can enable the critical thinker to produce reasonable decisions. There are several conceptions of CT (Hitchcock 2018). Ennis (2018a) considers that those conceptions are not significantly different from each other and that leads into deriving similar lists of abilities and dispositions from them.

Ennis's work (e.g., Ennis 1996a, 2018a) has involved the dissection of CT into abilities (e.g., judge the credibility of a source, analyze arguments) and dispositions (e.g., try to be well-informed, be alert for alternatives). Throughout his academic career, Ennis has refined his list to make it more rigorous and comprehensive. There is no need to list here those abilities and dispositions. His most updated list can be found in his recent publications (e.g., Ennis 2018a) as well as on a website developed by him and Sean F. Ennis, which can be accessed through the following link: http://criticalthinking.net/index.php/longdefinition/ (Ennis 2018b).

Based on a review of the literature of CT, Hitchcock (2018) differentiates between two kinds of dispositions, namely initiating dispositions (e.g., open-mindedness, trust in reason, seeking the truth) and internal dispositions (e.g., the disposition to formulate the issue clearly and to maintain focus on it). Hitchcock also describes a number of abilities (e.g., observational, questioning, inferential, and argument analysis abilities) and highlights the importance of *knowledge* of CT concepts, of CT principles, and of the subject matter of the thinking.

A teacher may borrow from lists of knowledge, abilities, and dispositions of CT such as those developed by Ennis, Hitchcock, or others and use them as resources while guiding students in a NOS lesson. Those lists can become a comprehensive frame of reference for both the teacher and the student and can act as a mediator for one to penetrate more deeply into one's thinking. Students can thus engage in deeper thinking about NOS when they are guided to practice some of those CT-related abilities and dispositions and to reflect on the underlying knowledge of CT concepts and principles—all within the context of NOS. Consequently, from a pedagogical perspective, those lists are appealing because they provide a practical starting place for teaching NOS critically. They have the potential (1) to foster a framework for the development of educational programs, standards, and resources and (2) to facilitate in-depth discussions about NOS.

Fifth, CT as a framework for addressing NOS would make the learning of NOS more authentic. When philosophers, sociologists, historians of science, and science educators engage in philosophical debates about NOS, CT about NOS is often at the foreground of their debates. They engage in making decisions about their views, about others' views, and about what to accept or not to accept. As a result, the NOS-related positions produced are quite divergent and competing.

The science education community is well aware of the undesired consequences of teaching scientific knowledge without regard for the *processes* by which that knowledge is produced. For instance, detaching scientific content knowledge from the processes promotes a naive view of the nature of scientific inquiry resulting in an image of science as a collection of isolated facts (Schwab 1962). As a remedy, the science education community reached a broad agreement on the importance and role of inquiry in the teaching and learning of science (e.g., Krajcik et al. 1998; NRC 1996; Roth 1995; Schwab 1962; Tamir 1983). Using the same logic, detaching the substantive NOS content from the process of its development promotes a naive view of philosophy of science: It portrays an image of NOS as a collection of isolated facts. It also promotes a nonauthentic image of the philosophical discourse on NOS and the process of how the substantive content of NOS develops.

CT as a framework for addressing NOS would bring CT into the foreground of school NOS, moving the substantive NOS content into the background. Rather than working towards developing adequate NOS understandings among students, the focus would be placed on the *process* as students would be guided to practice making judgments on NOS views, or at the minimal level develop a *mindset* so that they could eventually make informed judgments on NOS views.

As an example, a secondary student could be considered to have more authentic (and deeper) understandings of McComas's proposed NOS-related idea that "science is tentative, durable and self correcting" when she explores this idea *critically* compared to when she explores it non-critically, because critical exploration would entail learning not only about the NOS-related idea per se but also the *process* by which this NOS-related idea is explored in philosophical circles. Such a proposal makes the position of CT foundational: CT rather than the substantive NOS content gets situated in the foreground of school NOS, while NOS as a set of concepts/ideas moves from the foreground of NOS instruction into the background.

Having discussed five reasons for why students need to develop their NOS understandings critically, I now place the spotlight on *how* to teach NOS through the lens of CT.

10.3 Teaching NOS Critically

Based on the discussion in the previous section, I now outline a procedure that could be useful in teaching NOS critically. For illustration, let us suppose that students in a secondary classroom would be guided to investigate McComas's proposed NOS-related ideas that "science is tentative, durable and self correcting" and that "evidence is required in science".

First, establish the necessary platform on which critical exploration of NOS can take place. This can be done by creating a background context so that discussions about NOS revolve around concrete situations. Abd-El-Khalick (2012b) has identified several contexts that science education researchers have relied upon in designing NOS interventions. For the purpose of elaborating an example, the context chosen would be socioscientific issues through which students can explore certain NOS-related idea(s). Having well-reasoned views of NOS can also support citizens in making decisions on socioscientific issues (Driver et al. 1996; Kolstø 2001a; Yacoubian 2015; Zeidler et al. 2002). So it is a two-way process.

For example, evolutionary biology and electromagnetic radiation are two content topics covered in high school science curricula. These lend themselves to a number of socioscientific issues such as the following:

(1) Whether creationism should be taught in high school science classes
(2) Whether new houses should be built next to high-voltage power lines.

Both issues are controversial and relevant to the lives of students. Hence, they could create a good context for NOS discussions. Both could be targeted from a NOS perspective, as well as from political, policy, aesthetics, ethical, health, and other perspectives. A teacher should guide the students to explore these issues from multiple perspectives, given that various perspectives could be valuable and one may eventually make use of a combination of them in making judgments. Nonetheless, I delimit my discussion to the NOS perspective here. I also believe that a teacher cannot guide the students to develop in-depth understandings of all the perspectives simultaneously. There is always choice involved in terms of which perspective will be the focus of discussion at a specific time, despite the fact that there could be room for integration among different perspectives.

Second, provide a NOS focus to the lesson. It is important that the exploration of one or more NOS-related ideas becomes a targeted focus of the lesson. Let us assume that we decide to focus the discussion of the first issue on *creationism and the tentative aspect of science* and that of the second issue on the *relationship between long-term exposure of magnetic fields of the type generated by high-voltage power lines and cancer incidence of children*. Two focused questions can be generated:

(Q1) To what extent are creationists' views on the origin of life tentative?
(Q2) To what extent does evidence suggest a relation between exposure of magnetic fields of the type generated by high-voltage power lines and cancer incidence of children?

A student needs to use her understandings of NOS in order to engage in a meaningful discussion and answer Q1 and Q2. In particular, she needs to use her understandings of the terms "tentativeness" and "relation" respectively. In these situations, the student is being asked to use her NOS understandings to make judgments.

Third, develop a learning activity that can engage students in critical exploration of the NOS-related ideas in question. In order to appreciate the complexity of the issues, a student needs to be exposed to the different viewpoints concerned. For instance, the student could be guided to be exposed to contradictory philosophical positions on creationism and the tentative aspect of science as she thinks about Q1 and she may be exposed to contradictory scientific research findings on the relationship between long-term exposure of magnetic fields of the type generated by high-voltage power lines and cancer incidence of children as she thinks about Q2. I acknowledge that students at the precollege level are often not in a position of being able to read primary literature in philosophy and science. Exposing students to read secondary literature or adapted versions of primary literature (Yarden et al. 2001) might be ways of introducing the controversies. It is worth noting that the learning activity could also take other forms such as asking students to do some background research by themselves.

Fourth, engage students in critical exploration of NOS while facilitating explicit reflective discussions. When teachers engage their students in explicit reflective discussions on NOS, they consider the development of their students' NOS understandings as target cognitive instructional outcome. When students will be guided to explore NOS critically within the context of explicit reflective discussions, CT is the particular type of inquiry that students would need to engage in as they learn how to make decisions on NOS views. Hence, thinking critically about NOS would become a target instructional outcome.

As students engage in critical exploration of NOS, a teacher needs to explicitly target the development of CT-related knowledge, abilities, and dispositions among students. Teachers need to create opportunities where students could enhance their CT by understanding concepts and criteria of CT, developing the required abilities and the dispositions, as well as applying them in decision making (Abrami et al. 2008).

Considering our example, in order to be able to formulate her positions on Q1 and Q2, and in order to formulate them well, the student needs to be provided with opportunities to analyze and evaluate what the terms "tentativeness" and "relation" mean in these contexts and what significance they have. These are key terms around which philosophical discussion *about* NOS can happen. Specifically, reflecting on these terms can respectively help students develop deeper understandings about McComas's proposed NOS-related ideas that "science is tentative, durable and self correcting" and that "evidence is required in science" within the context of the chosen foci, socioscientific issues, and the content topics.

Consequently, in order for the student to be able to answer Q1 and Q2 and answer them well, she needs to think in the first place about more fundamental questions. These questions could be as follows:

(Q1a) How is science tentative?

(Q2a) In what circumstances could a causal inference between variables be considered a strong one?

Note that in Q1a the focus is being placed on developing understandings of tentativeness in science, whereas in Q2a the focus is on developing understandings of causal inference. Note how students practice making decisions: Through Q1a and Q2a they are encouraged to practice making judgments *about* NOS as there is no single view out there about tentativeness in science and what that means within the context of creationism. The debate between Ruse (1982) and Laudan (1982) is quite illustrative in that regard. Moreover, there is no clear-cut point in deciding when causal inference between variables can be considered strong. In fact, this also partly explains the availability of contradictory findings in the literature when it comes to Q2.

Accordingly, Q1a and Q2a are designed so that students can engage in a critical analysis of some of these interpretations and try to make judgments on them. As far as Q1a is concerned, once the students have given some thought about tentativeness in science, they can be guided to apply their understandings of tentativeness to evaluate the extent to which creationists' views on the origin of life could be subject to change and thus defend a position regarding Q1. This might require the student to analyze accounts of tentativeness in the context of the issue in question with the purpose of developing an understanding of the context, and then to apply her understanding of tentativeness to this context.

Concerning Q2a, research studies that explore a relationship between long-term exposure of magnetic fields of the type generated by high-voltage power lines and cancer incidence of children are usually epidemiological in nature, and many of them are designed as case–control studies. Experimental studies on humans are rare. Q2a is formulated so that students can be guided to develop understandings of causal generalizations. Once the students have given some thought to causal generalizations, they are in a better position to think about Q2. Here they are guided to use their understandings of causal relationships to evaluate the extent to which evidence supports a relationship between long-term exposure of magnetic fields of the type generated by high-voltage power lines and cancer incidence of children.

One or a combination of CT dispositions, abilities, and their underlying concepts discussed in the previous section could be targeted here. As students through Q1a and Q2a engage in critical exploration of some of the interpretations on tentativeness in science as well as causal generalizations, they can be guided to practice CT abilities such as *inferential* and *argument analysis* abilities (Ennis 2018a; Hitchcock 2018). As further teaching resources, a teacher, for instance, can make use of the detailed lists of criteria under each of these abilities developed by Ennis (2018b). Students can also be guided to reflect upon the underlying concepts of these abilities. Furthermore, they can internalize CT dispositions such as open-mindedness and being alert for alternatives (Ennis 2018a; Hitchcock 2018).

A final note: As previously stated, the aim of engaging students in such lessons is not to prepare them to become philosophers of science. Guiding students to practice making decisions on NOS views should be done in developmentally appropriate ways. Conducting such lessons would be feasible only if during earlier years of schooling, students are exposed to the necessary prerequisites on the learning trajectory. It is beyond the scope of this chapter to provide a full-fledged developmental pathway for NOS learning. Consulting the literature on developmental research can be helpful to identify certain elements helpful in designing a developmental trajectory for NOS learning using CT as a progression unit. This is open for more research.

10.4 Feasibility Study

A feasibility study was conducted on the basis of the ideas discussed in this chapter. An instructional resource package was developed for teaching NOS critically. The package included a NOS lesson that was prepared using the four steps described in the previous section. The health effects of low-intensity electromagnetic radiation from cell phones were chosen as a topic for students to engage in exploration of whether cell phone usage should be regulated by law. Two pieces of adapted primary literature were also developed, which were used as learning activities.

A framework proposed by Nistor et al. (2010) was used to study experienced science teachers' views of the resource package. The teachers were regarded as partners in the production of the resource. Nonetheless, not all feedback received from them led into product modularity, or changes in the resource as product. Some of the feedback was used to generate recommendations for in-service science teacher education.

Seventeen experienced secondary science teachers from three schools in Lebanon were enrolled in the study. The schools where the teacher worked offered the Lebanese as well as international programs and provided ongoing professional development opportunities for their teachers. The average duration of school teaching experience of the participants was 15.1 years, while their average duration of science teaching experience at the secondary level was 12.8 years.

The teachers participated in a 4-hour-workshop, led by the researcher, to get introduced to the draft resource. The researcher utilized a learning cycle to introduce the package. Next, teachers were asked to complete a questionnaire that contained a list of open-ended questions that aimed at collecting qualitative data to elicit feasible and nonfeasible features of the resource as well as recommendations for improvement. Semistructured in-depth interviews were also conducted with 16 participants. Interviews were audio recorded and transcribed. Questionnaires and interview questions were pilot-tested before being used. All data were coded and analyzed qualitatively using Miles and Huberman's (1994) approach.

The majority of the participants found the resource to be somewhat feasible for inclusion in a secondary-level science course (Table 10.1).

Table 10.2 shows the features of the resource that the participants thought made the lesson feasible and those that made it nonfeasible. Table 10.3 highlights every

Table 10.1 Number of participants who found the resource feasible, somewhat feasible, and nonfeasible

Categories	Number of participants
Feasible	1
Somewhat feasible	15
Nonfeasible	1

Table 10.2 The feasibility and nonfeasibility of features of the resource as identified by the participants

	Features																
Part.	rel	ali	nos	cri	eng	int	lan	dif	res	str	tim	pre	siz	con	ass	lev	rea
1	+	+							–		–					–	
2				–			+			+						–	
3		+							+		–						
4	+			–							–					–	–
5							+	+			–	–					
6	+			–			–	–			–					–	
7			+								–						
8	+					+								–			
9	+	–		+							–						
10		+	–			+					–			–			
11					+						–				–		
12				+							–			–	–		
13	–													–			
14			+	+										–			
15											–			–			
16		+									–	–	–				
17	+	–															

Note. rel relevant to students' lives, *ali* alignment (or its lack of) between curriculum and the resource, *nos* nature of science-related content, *cri* critical thinking, *eng* engaging, *int* interesting, *lan* language, *dif* difficulty level, *res* resources, *str* structure and organization of the lesson, *tim* time, *pre* preparation for teaching, *siz* class size, *con* controversial elements, *ass* assessment, *lev* learning levels and/or various needs of students in the same class, *rea* reading; + denotes a feature that makes the resource feasible; – denotes feature that makes the resource nonfeasible

feature concerning feasibility that was raised by at least four participants and illustrates sample responses. The number *four* was arbitrary and the rationale was based on the fact that about a quarter of the participants were pointing to that particular feature.

A number of features were identified through the teachers' recommendations, important to be considered when preparing similar resources and/or developing professional development programs. They are (1) relevance of the lesson to the lives of students; (2) alignment of the lesson with the science curriculum being used; (3) adaptation of the lesson, in general, and the background context, in particular, to the learning levels/needs of various students; (4) extent to which the lesson is engaging

Table 10.3 Sample participant responses concerning feasibility for each feature referred to by at least four participants

Features	fea+	fea−	Recommendations to make the lessons more feasible
rel	[The lesson is] related to our everyday life problems or issues that can somewhat enhance the curiosity of students to know more (Q4).	They [the studies] are projected onto a certain type of countries and cannot be generalized (Q13).	To generalize these studies (Q13).
ali	The idea of e.m.r. [electromagnetic radiation] is already mentioned in many physics books (Q10).	… it can't be applied in the course I teach (Q9, I9).	Include NOS objectives in the curriculum (Q1).
			Prepare different methods to start different chapters or topics (Q17).
cri	We can lead our students to critical thinking during explanation in class… (Q9, I9).	These lessons require analysis skills which some students might be weak at (Q2).	To make the lessons feasible for everyone, the teacher should guide the students in all the parts especially those related to tables and drawing conclusions from data (Q2).
		Some students are not able to analyze articles, compare, and contrast results (I6).	
tim		…time limitations imposed by closed-ended curriculum set by the Ministry of Education (Q16).	Two teachers (eg biology and physics teachers) involved in one lesson? (Q1).
con		The contradictory conclusions reached even when based on the same data might confuse students (Q8). … they are not up to the level where they can manipulate different criteria. They need to memorize something (I8).	Select a less controversial idea, where we could teach the nature of science using much older research that is more conclusive than cellular phone usage which hasn't been studied enough (Q10).
		… too controversial! Would leave students with the impression that science is not able to reach results conclusively (Q10, I10).	
lev		Presence of students with learning difficulties (e.g., dyslexic) (Q1).	Adapt the articles to students with learning difficulty who we believe we could do a great deal of critical thinking (e.g., more diagrams/pictures, less reading) (Q1).

Note. Definitions of features are found in Table 10.2; *Q* Questionnaire, number following Q represents participant number; *I* Interview, number following I represents participant number in nature; (5) involvement of scientific content knowledge; (6) involvement of NOS-related content; (7) involvement of elements that engage students in decision making; (8) discussions; (9) CT; (10) organization of the lesson; (11) details of the background context; (12) time limitations; (13) reading required from students; and (14) controversial elements involved in the lesson.

The study revealed a number of teacher challenges related to what CT is and how to teach for it. In addition, some participants found reading to be a challenge for their students. They suggested reducing the amount of reading and replacing it by other means. Such a position assumes that reading is considered merely a tool and is situated outside science rather than being inherent to the thinking process (Norris and Phillips 2003). Finally, controversial elements make the NOS lesson authentic. Nonetheless, many teachers considered their presence problematic. The view that students might lose trust in science as a result of being exposed to controversial issues is raised by science educators (e.g., Driver et al. 1996; Kolstø 2001b).

This study made possible a list of teacher-generated features helpful in designing similar instructional resources and in developing effective professional development modules for in-service teachers. The teachers' generally positive views provide grounds for optimism. The ideas developed in this chapter are worth pursuing further. They have the potential to be bases for research and development agenda.

References

Abd-El-Khalick, F. (2012a). Nature of science in science education: Towards a coherent framework for synergistic research and development. In B. J. Fraser, K. Tobin, & C. McRobbie (Eds.), *Second international handbook of science education* (pp. 1041–1060). New York: Springer. https://doi.org/10.1007/978-1-4020-9041-7_69.

Abd-El-Khalick, F. (2012b). Examining the sources for our understandings about science: Enduring conflations and critical issues in research on nature of science in science education. *International Journal of Science Education, 34*, 353–374. https://doi.org/10.1080/09500693.2011.629013.

Abrami, P. C., Bernard, R. M., Borokhovski, E., Wade, A., Surkes, M. A., Tamim, R., & Zhang, D. (2008). Instructional interventions affecting critical thinking skills and dispositions: A stage 1 meta-analysis. *Review of Educational Research, 78*, 1102–1134.

Akerson, V. L., & Hanuscin, D. L. (2007). Teaching nature of science through inquiry: Results of a 3-year professional development program. *Journal of Research in Science Teaching, 44*, 653–680. https://doi.org/10.1002/tea.20159.

Akerson, V. L., Abd-El-Khalick, F., & Lederman, N. G. (2000). Influence of a reflective explicit activity-based approach on elementary teachers' conceptions of nature of science. *Journal of Research in Science Teaching, 37*, 295–317. https://doi.org/10.1002/(SICI)1098-2736(200004)37:4<295::AID-TEA2>3.0.CO;2-2.

Akerson, V. L., Buck, G. A., Donnelly, L. A., Narguand-Joshi, V., & Weiland, I. S. (2011). The importance of teaching and learning nature of science in early childhood years. *Journal of Science Education and Technology, 20*, 537–549. https://doi.org/10.1007/s10956-011-9312-5.

Bell, R. L., Blair, L. M., Crawford, B. A., & Lederman, N. G. (2003). Just do it! Impact of a science apprenticeship program on high school students' understandings of the nature of science and scientific inquiry. *Journal of Research in Science Teaching, 40*, 487–509. https://doi.org/10.1002/tea.10086.

Driver, R., Leach, J., Millar, R., & Scott, P. (1996). *Young people's images of science*. Philadelphia: Open University Press.
Duschl, R. A., Schweingruber, H. A., Shouse, A. W., Committee on Science Learning, & National Research Council. (2007). *Taking science to school: Learning and teaching science in grades K-8*. Washington, DC: National Academies Press.
Ennis, R. H. (1989). Critical thinking and subject specificity: Clarification and needed research. *Educational Researcher, 18*, 4–10. https://doi.org/10.3102/0013189X018003004.
Ennis, R. H. (1996a). *Critical thinking*. NJ: Prentice Hall.
Ennis, R. H. (1996b). Critical thinking dispositions: Their nature and assessability. *Informal Logic, 18*, 165–182.
Ennis, R. H. (2018a). Critical thinking across the curriculum: A vision. *Topoi, 37*, 165–184.
Ennis, R. H. (2018b). *The nature of critical thinking*. http://criticalthinking.net/index.php/longdefinition/. Accessed online 19 Sept 2018.
Gunn, T. M., Grigg, L. M., & Pomohac, G. A. (2007). *Critical thinking in science education: Can bioethical issues and questioning strategies increase scientific understanding?* Paper presented at the ninth international history, philosophy & science teaching conference. University of Calgary. http://www.ucalgary.ca/ihpst07
Hitchcock, D. (2018). Critical thinking. In E. N. Zalta (Ed.), *The Stanford encyclopedia of philosophy (fall 2018 edition)*. Stanford: Stanford University. https://plato.stanford.edu/archives/fall2018/entries/critical-thinking/. Accessed online Sept 2018.
Keating, D. P. (1988). *Adolescents' ability to engage in critical thinking*. [S.l.]: Distributed by ERIC Clearinghouse.
Khishfe, R. (2008). The development of seventh graders' views of nature of science. *Journal of Research in Science Teaching, 45*, 470–496. https://doi.org/10.1002/tea.20230.
Khishfe, R., & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth graders' views of nature of science. *Journal of Research in Science Teaching, 39*, 551–578. https://doi.org/10.1002/tea.10036.
Kim, S. Y., & Irving, K. E. (2010). History of science as an instructional context: Student learning in genetics and nature of science. *Science & Education, 19*, 187–215. https://doi.org/10.1007/s11191-009-9191-9.
King, P. M., & Kitchener, K. S. (1994). *Developing reflective judgment: Understanding and promoting intellectual growth and critical thinking in adolescents and adults*. San Francisco: Jossey-Bass.
Kolstø, S. D. (2001a). Scientific literacy for citizenship: Tools for dealing with the science dimension of controversial socioscientific issues. *Science Education, 85*, 291–310. https://doi.org/10.1002/sce.1011.
Kolstø, S. D. (2001b). To trust or not to trust,… ' -pupils' ways of judging information encountered in a socio-scientific issue. *International Journal of Science Education, 23*, 877–901. https://doi.org/10.1080/09500690010016102.
Krajcik, J., Blumenfeld, P. C., Marx, R. W., Bass, K. M., Fredricks, J., & Soloway, E. (1998). Inquiry in project-based science classrooms: Initial attempts by middle school students. *The Journal of the Learning Sciences, 7*, 313–350. https://doi.org/10.1207/s15327809jls0703&4_3.
Kuhn, D. (1999). A developmental model of critical thinking. *Educational Researcher, 28*, 16–25+46. https://doi.org/10.3102/0013189X028002016.
Laudan, L. (1982). Commentary: Science at the bar-causes for concern. *Science, Technology & Human Values, 7*(41), 16–19.
Lederman, N. G. (2004). Syntax of nature of science within inquiry and science instruction. In L. B. Flick & N. G. Lederman (Eds.), *Scientific inquiry and nature of science* (pp. 301–317). Dordrecht: Kluwer.
Lipman, M. (2003). *Thinking in education* (2nd ed.). Cambridge: Cambridge University Press.
Matthews, M. R. (1994). *Science teaching: The role of history and philosophy of science*. New York: Routledge.

McComas, W. F. (Ed.). (1998). *The nature of science in science education: Rationales and strategies*. New York: Kluwer Academic Publishers.
McComas, W. F. (2004). Keys to teaching the nature of science. *The Science Teacher, 71*(9), 24–27.
Miles, M. B., & Huberman, A. M. (1994). *Qualitative data analysis: An expanded sourcebook* (2nd ed.). California: SAGE.
National Research Council [NRC]. (1996). *National science education standards*. Washington, DC: National Academic Press. Retrieved from http://www.nap.edu/openbook.php?record_id=4962
Nicoll, B. (1996). *Developing minds: Critical thinking in k-3*. Paper presented at the California Kindergarten Conference, San Francisco, CA. Distributed by ERIC Clearinghouse.
Nistor, N., Dehne, A., & Drews, F. T. (2010). Mass customization of teaching and training in organizations: Design principles and prototype evaluation. *Studies in Continuing Education, 32*, 251–267. https://doi.org/10.1080/0158037X.2010.517996.
Norris, S. P., & Phillips, L. M. (2003). How literacy in its fundamental sense is central to scientific literacy. *Science Education*, *87*, 224–240. https://doi.org/10.1002/sce.10066.
Osborne, J., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. (2003). What "ideas-about-science" should be taught in school science? A Delphi study of the expert community. *Journal of Research in Science Teaching, 40*, 692–720. https://doi.org/10.1002/tea.10105.
Paraskevopoulou, E., & Koliopoulos, D. (2011). Teaching the nature of science through the Millikan-Ehrenhaft dispute. *Science & Education, 20*, 943–960. https://doi.org/10.1007/s11191-010-9308-1.
Roth, W. M. (1995). *Authentic school science: Knowing and learning in open-inquiry science laboratories*. Dordrecht: Kluwer.
Ruse, M. (1982). Creation science is not science. *Science, Technology & Human Values, 7*(40), 72–78.
Sadler, T. D. (Ed.). (2011). *Socio-scientific issues in the classroom: Teaching, learning and research*. Dordrecht: Springer.
Schwab, J. J. (1962). The teaching of science as enquiry. In J. Schwab & P. Brandwein (Eds.), *The teaching of science*. Cambridge, MA: Harvard University Press.
Schwartz, R. S., Lederman, N. G., & Crawford, B. A. (2004). Developing views of nature of science in an authentic context: An explicit approach to bridging the gap between nature of science and scientific inquiry. *Science Education, 88*, 610–645. https://doi.org/10.1002/sce.10128.
Siegel, H. (1988). *Educating reason: Rationality, critical thinking, and education*. New York: Routledge.
Tamir, P. (1983). Inquiry and the science teacher. *Science Education, 67*, 657–672. https://doi.org/10.1002/sce.3730670513.
Yacoubian, H. A. (2015). A framework for guiding future citizens to think critically about nature of science and socioscientific issues. *Canadian Journal of Science, Mathematics, and Technology Education, 15*(3), 248–260.
Yacoubian, H. A., & BouJaoude, S. (2010). The effect of reflective discussions following inquiry-based laboratory activities on students' views of nature of science. *Journal of Research in Science Teaching, 47*, 1229–1252. https://doi.org/10.1002/tea.20380.
Yarden, A., Brill, G., & Falk, H. (2001). Primary literature as a basis for a high-school biology curriculum. *Journal of Biological Education, 35*(4), 190–195.
Zeidler, D. L., Walker, K. A., Ackett, W. A., & Simmons, M. L. (2002). Tangled up in views: Beliefs in the nature of science and responses to socioscientific dilemmas. *Science Education, 86*, 343–367. https://doi.org/10.1002/sce.10025.