Science & Education (2020) 29:443–463
https://doi.org/10.1007/s11191-020-00108-8

ARTICLE

From Inquiry-Based Science Education to the Approach Based on Scientific Practices

A Critical Analysis and Suggestions for Science Teaching

Antonio García-Carmona[1]

Published online: 29 February 2020

Abstract
For years, inquiry-based learning has been conceived of and promoted as one of the best approaches to learning science. However, there is currently a movement within the science education community that suggests promoting science learning based on scientific practices, instead of inquiry, because in this way, science learning would be more coherent with the enterprise that is science. But, are there well-founded reasons to work towards this shift, or is it just a new terminology with which to refer to inquiry? In order to respond to this question, firstly, the main arguments which support science education based on scientific practices are presented. Secondly, an analysis is made in order to determine the extent to which the approach based on scientific practices is innovative with respect to the inquiry approach. Thirdly, nature of the inquiry and scientific practice constructs is analyzed. All of this is done from a critical and reflective view. Finally, some reflections and suggestions are made in relation to practice-based science education.

Keywords Science standards · Scientific inquiry · Scientific practices · Science education

> Distinctions between the cognitive and the social, the technical and the career-relevant, the scientific and the non-scientific are constantly blurred and redrawn in the laboratory (Knorr-Cetina 1981, p. 23).

1 Introduction

As in other areas of knowledge, changes in approaches, models, and paradigms constitute a usual and necessary dynamic for the development of science education. Most such changes are not,

✉ Antonio García-Carmona
garcia-carmona@us.es

1 Departamento de Didáctica de las Ciencias Experimentales y Sociales, Facultad de Ciencias de la Educación, Universidad de Sevilla, Calle Pirotecnia S/N, 41013 Sevilla, Spain

however, immediate, since they have to coexist and compete with the previous approaches for some time. Thus, sometimes a new approach begins to be promoted with respect to another which had attained a high level of consensus or acceptance in the international science education community. In my opinion, this is what is now happening with the pedagogical movement which assumes scientific practices instead of inquiry as the ideal framework for learning science.

The approach based on scientific practices has mainly emerged in the context of education in the USA (Bybee 2011; Ford 2015; NGSS Lead States, 2013; National Research Council [NRC] 2012; Osborne 2014), and it is starting to make some impact in other many countries, such as Canada (e.g., Öberg and Campbell 2019), South Korea (e.g., Lin et al. 2016; Yoon et al. 2014), Taiwan (e.g., Cheng et al. 2019), Jordan (e.g., Malkawi and Rababah 2018), Netherlands (e.g., Prins et al. 2018), and Spain (Crujeiras-Pérez and Jiménez-Aleixandre 2018; Jiménez-Liso et al. 2019). However, in some of these countries, such as Spain, the scientific practice term has begun to be used in the community of science teacher educators, although the official science curriculum for primary and secondary education (Education Ministry 2014, 2015) does not refer to it. The closest thing to it is included in a block of cross-cutting contents called *initiation to scientific activity* in the primary science curriculum, and scientific activity in the secondary science curriculum, in which some inquiry abilities are suggested. For example, within that block for primary education, one of the learning standards establishes that "students conduct small inquiries posing problems, hypothesizing, selecting materials, obtaining conclusions and communicating them." In other European countries, such as UK, the science curriculum also does not refer to scientific practices (Department for Education 2013). Instead, it is employed the phrase "practical scientific methods, processes and skills" to refer to those school tasks related to *scientific inquiry*. Similarly, the current Australian science curriculum (Australian Curriculum, Assessment and Reporting Authority [ACARA] 2015) also continues to refer to science inquiry skills as one of the elemental strands of science.

Consequently, I have wondered: are there substantial reasons for justifying this change of didactic approach, or it is just a new terminology with which to refer to the usual school science activities based on inquiry? In order to respond this question, in this article I shall (i) look at the main reasons that have motivated the proposal for promoting practice-based science learning, (ii) present arguments that question the need for that change of didactic approach, and (iii) assess the said reasons based on an analysis of nature of the two constructs. This shall be done from a critical and reflective view through a review of the more relevant authors who support that educational change, the main reform documents in which it is proposed (i.e., K–12 Framework NRC 2012 and NGSS Lead States, 2013), and which are cited in the majority of international proposal aligned with science-based science education,[1] as well as of literature on science studies, history, philosophy, and sociology of science. I shall conclude with some suggestions for expanding the predominant conceptualization of practice-based science education currently.

[1] K-12 Framework NRC (2012) document is cited in the majority of the current international studies on practice-based science education (see, for example, the references cited above). In addition, that document is mentioned in the Science Framework of PISA 2015 and 2018 Organization for Economic Co-operation and Development [OECD] (2017, 2019), which is an international program that currently affects 76 countries.

2 Why Teach Science Based on Scientific Practices?

For years, there has been a broad international consensus that scientific inquiry is one of the most appropriate approaches to learning science (Abd-El-Khalick et al. 2004; Harlen 2012; OECD 2017, 2019; Rocard et al. 2007), especially if the students are to learn science by doing science (Hodson 2014). Although the literature places the origin of this didactic approach in the early twentieth century with the American John Dewey (1859–1952), it was not until the beginning of the 1960s with the work of Joseph J. Schwab (1909–1988) that scientific inquiry began to take on importance in the proposals for science teaching in the USA (Barrow 2006; Bybee 2011).

At that time, the focus of US science curricula was on the so-called processes of science. The intention was to banish the rote application of the steps of the "scientific method" that prevailed in science classes. The aim of shifting the focus to the processes of science was to emphasize that students learnt specific and fundamental processes such as observing, clarifying, measuring, inferring, and predicting, at the same time as they were learning the concepts of the scientific discipline (Bybee 2011, p. 14). But, apparently, this perspective led to the learning of concepts being left unattended in favor of the processes. Consequently, the incorporation of scientific inquiry into the educational context was aimed at stressing the learning of science concepts by using the skills of inquiry (ibid.). In other words, a teaching strategy was being encouraged whose focus was on using activities and inquiries to learn science by doing science.

Since then, the approach of inquiry-based science learning has been taken into account in the majority of science education plans in the world (Abd-El-Khalick et al. 2004; OECD 2007; Ramnarain 2018; Rocard et al. 2007; Rundgren 2018; Zhang 2016), and this has evolved with multiple meanings or different proposals for its implementation in class (Minner et al. 2010; Rönnebeck et al. 2016). One can say therefore that the conception of scientific inquiry for use in school is not univocal, and that the debate about what is the most appropriate didactic strategy to follow in a science class is still open (Bevins and Price 2016; Furtak et al. 2012; Hmelo-Silver et al. 2007; Kirschner et al. 2006; Zhang 2016).

In the 1990s, the National Science Education Standards (NRC 1996) established scientific inquiry in the following terms:

> Inquiry is a multifaceted activity that involves making observations; posing questions; examining books and other sources of information to see what is already known; planning investigations; reviewing what is already known in light of experimental evidence; using tools to gather, analyze, and interpret data; proposing answers, explanations, and predictions; and communicating the results. Inquiry requires identification of assumptions, use of critical and logical thinking, and consideration of alternative explanations (p. 23).

From that time onwards until the publication of the NGSS Lead States (2013), which itself was based on what had been established by the NRC (2012),[2] the different activities or actions mentioned above were considered to be desirable skills and abilities for students to learn science through inquiry NRC (2000). All this has led in recent years to a vast quantity

[2] It is necessary to clarify that NGSS are not an official mandatory for science education in the USA. Indeed, according to the National Science Teaching Association (NSTA, https://ngss.nsta.org/About.aspx), various states have not adopted the NGSS, and others have adopted them only partially. Even so, I consider that the NGSS is possibly the most coherent or high-profile document for analyzing science education in the USA. In addition, according to the literature on science education, the NGSS are very influential in other many countries.

of international research related to the inquiry-based approach (see, for example, the recent and interesting reviews by Rönnebeck et al. (2016) and Zhang (2016) of the literature about it). While research shows that inquiry-based science education favors, for instance, student active thinking, process skills and positive attitude to science (Anderson 2002; Minner et al. 2010), this also reveals, for instance, the difficulties students have to elaborate complete scientific explanations of phenomena based on evidence and reasoning and to engage in high-quality argumentation (Rönnebeck et al. 2016). In addition, research shows difficulties in training science teachers to be capable of putting the inquiry approach into practice (García-Carmona et al. 2017; Crawford 2007; Newman et al. 2004; Kim and Tan 2011; Yoon et al. 2012).

In order to explain the possible causes for scientific inquiry not being as effective a framework for learning science as might have been expected, some authors, such as Bybee (2011) and Osborne (2014) among others, have focused on there being an inadequate or limited understanding of the approach. One example has to do with the oversimplifications that were made of scientific inquiry in science education (Osborne 2014). Indeed, despite inquiry approach encourages the learning of science content by using the skills of scientific inquiry (Bybee 2011), this approach has been frequently interpreted more as a process than as a means for learning science (Asay and Orgill 2010). In addition, inquiry has been identified with simple laboratory experiences, performed uncritically and mechanically, as if they were "cooking recipes" (García-Carmona et al. 2018).

Another possible cause would be the polysemy existing in the literature regarding the term scientific inquiry. The review by Minner et al. (2010) found that "inquiry" is often used interchangeably to refer to (1) what scientists do (scientific methodology), (2) what students do who are learning science with strategies inspired by scientific work (learning process), and (3) what teachers do to implement the school science curriculum from an inquiry-based perspective (teaching strategy or method). Probably, this variety of meanings has hindered any appropriate conceptualization of inquiry in its use in school.[3] For Osborne (2014), the usual implementation of inquiry-based approach in science class has led to doing science being inappropriately identified with learning science, despite the two activities being very different both in purpose and in execution. Michaels et al. (2008) have a similar perception about the term inquiry, and they also prefer to talk about "scientific practices" instead of "inquiry" in their book for science education in grades K–8. These authors argue that "science as practice involves doing something and learning something in such a way that the doing and the learning cannot really be separated" (ibid., p. 34). From this perspective, Michaels et al. (2008) assume that "scientific practices" is an approach broader than "inquiry" and consider the latter *a particularly important form* of scientific practice. But, what is really the meaning of "inquiry" in the practice-oriented framework?[4]

Osborne (2014) also intends to deepen in what involves engaging in scientific practices with a review of important contributions from the philosophy of science and from psychology. First, he highlights that the main purpose of school science education is not

[3] This is referred in K–12 Framework (NRC 2012) as follows: "(...) attempts to develop the idea that science should be taught through a process of inquiry have been hampered by the lack of a commonly accepted definition of its constituent elements" (p. 44).

[4] In the K–12 Framework (2012) document, the term "(scientific) inquiry" is mentioned numerous times; however, unlike previous standards NRC (1996), what should be understood by "inquiry" within the practice-based framework is not given (or, at least, not explicitly).

to train students to do science, and he then concludes that engaging in practice only has significance if (ibid., p. 183): (a) it helps students to develop a deeper and broader understanding of what we know, how we know, and the epistemic and procedural constructs that guide the practice of science; (b) if it is a more effective means of developing such knowledge; and (c) it presents a more authentic picture of the endeavor that is science.

It has been attempted to reflect all these arguments in the US latest standards for science education (NGSS Lead States 2013), in which scientific practices have relegated inquiry to a secondary plane compared with the prominence it had in previous standards (NRC 1996, 2000). However, the supposedly greater didactic pertinence of practice-based science education is yet to be seen, in comparison with the large amount of empirical research around the world related to science education as inquiry (Minner et al. 2010; Rönnebeck et al. 2016; Zhang 2016). In addition, when consulting the NGSS's foundations and suggestions to teach science through scientific practices, I recognize that it is difficult to find significant differences with respect to inquiry-based approaches. This perception is also observed among science educators, as Furtak and Penuel (2019) point out: "We have both found ourselves, on multiple occasions, in rooms of educators who ask —quite understandably— how the list of eight science and engineering practices differs from the science inquiry standards" (p. 172). According to Larkin (2019, p. 1295), it possibly can be due, among other reasons, to a robust vision of science pedagogy is markedly absent from the NGSS Lead States (2013) and K–12 Framework (NRC 2012) documents.[5]

Ford (2015) also refers to the latter as follows:

> At first glance, this list [referring to the eight scientific practices articulated in NGSS Lead States (2013)] may seem to suffer from the same issue as "inquiry". It is not clear whether and how these eight activities capture the fundamental aspects of science, and whether they are necessary or sufficient to produce scientific knowledge. Moreover, what is to prevent these activities from being interpreted as an issue of semantics, with no practical difference between these and "scientific method" or "inquiry?" (p. 1042; the brackets are mine)

Ford (2015) then argues that scientific practice approach has been differentiated from its predecessors in that (1) they require specific knowledge to engage them, so they are distinct from domain-general skills; (2) they are not independent but rather are necessarily interrelated; and (3) they emphasize the connection between doing and learning. Although, he again notes that "these points do not get at the most consequential difference that 'practice' implies" (ibid., p. 1042). Consequently, it seems necessary to complement the consultation of NGSS Lead States (2013) with a review of the literature on science studies and science education in order to find arguments which justify the meaning and pedagogical benefits of practice-based science education (Erduran 2015).

Ford (2015) has carried out a literature review in that sense, and he essentially concludes that: "whereas the strategy behind 'scientific method' and 'inquiry' was to articulate regularities in reasoning and action and use these to define what students should think and do" (pp. 1042–1043), participating in scientific practices *does not mean following a series of*

[5] Larkin (2019) argues that "the choice to avoid specific pedagogy in standards documents seems understandable and reasonable because there is even less agreement on pedagogical approaches to teaching science than there is on the standards themselves (…). Yet, it seems paradoxical to try to develop a public understanding of science education [which is promoted in these documents] without some sense of how exactly that education is to take place" (p. 1296; the brackets are mine).

rules, but rather acquiring a capacity for the permanent evaluation and critique[6] in the construction of knowledge on nature. At this respect, I would like to make three brief comments. Firstly, while I fully agree that evaluation and critique are two fundamental processes in the construction of scientific knowledge, I think these have been also considered in the more genuine approaches for inquiry-based science education, as will be seen below. Secondly, in the Ford's analysis, "scientific method" and "inquiry" are treated as two similar educational approaches; however, inquiry is an approach much more sophisticated than the former (Tang et al. 2010). Thirdly, Ford insinuates in his argumentation that "inquiry" means "following a series of rules," but I have not found in the literature that inquiry-based science education suggests students should follow a series of "rules" when they engage in inquiry activities (see, for instance, the inquiry approaches proposed by Abell et al. (2006), Crawford (2000), Harlen (2012), Reiser et al. (2001), Tang et al. (2010), or White and Frederiksen (1998)). A very different issue is to employ some type of guidance or script in order to help students to perform inquiry activities (García-Carmona et al. 2017; Mäkitalo-Siegl et al. 2011; Mulholland et al. 2009; Vorholzer and von Aufschnaiter 2019). As with all other educational approaches, students always need some kind of support or scaffolding when they learn science through inquiry (Arnold et al. 2014; Hmelo-Silver et al. 2007; Sandoval 2005).

3 To What Extent is the Approach Based on Scientific Practices Really Innovative?

I think the arguments proposed by Ford (2015) for justifying practice-based science education are also applicable to inquiry-based science education, if it is assumed that scientific practices (in the context of NGSS Lead States (2013)) and inquiry (in the context of NRC (1996, 2000) are two constructs that deal with representing "what scientists do." Indeed, I find that the especial attention to evaluation and critique suggested by Ford for science teaching based on practices was already being promoted in the approach to science learning through inquiry. For example, in the NRC (1996), it can be read the following: "Students need the opportunity to evaluate and reflect on their own scientific understanding and ability (…)" (p. 88); "Students should evaluate their own results or solutions to problems, as well as those of under other children (…)" (pp. 137–138); or "Inquiry requires (…) consideration of alternative explanations" (p. 23).

Almost two decades ago, Reiser and co-workers also paid attention to evaluation and critique in their "The Biology Guided Inquiry Learning Environments (BGuILE)" project:

> Mid-investigation critiques provide students with opportunities to assess their progress while they can still revise and extend their work. Post-investigation assessments provide opportunities for students to compare their explanations (…). The evaluation criteria for critiques are established during the initial framing discussion in which students and teachers develop criteria for evaluating explanations. (…) these discussions are directed to focus students on assessing the causal coherence of their own and their peers' explanations (…). The goal is that students be able to reason about which explanations might be better than others and why (Reiser et al. 2001, pp. 293-294).

[6] Ford and co-workers define *critique* as "the social and intellectual source of a search for errors and the examination of multiple possibilities" (Forman and Ford 2014, p. 200). For more details on this, see Ford (2008).

Similarly, the renowned scholar Wynne Harlen refers in any way to the aspects above in her approach for inquiry-based science education. She emphasizes that moving from a traditional form of teaching science to one based on inquiry implies, among other changes, paying attention to:

> Arranging for group and whole class discussion of ideas and outcomes of investigations; given time for reflection (…); providing feedback on oral and written reports that enables students to know how to improve their work; and using assessment formatively as an on-going part of teaching and ensure student progress in developing knowledge, understanding and skills (Harlen 2012, p. 22).

Crawford (2014) also analyzed the change from inquiry to scientific practices, wondering if this constituted another form of rethinking the teaching of science as inquiry. She compared the two approaches as represented in the last two curricular reform documents for science teaching in the USA (Table 1), and highlights as one of the most notable differences the greater emphasis put on argumentation and modeling in the approach based on scientific practices (ibid., p. 523). However, she then adds that this emphasis on engaging in argumentation is not entirely a new one, in the sense that attention to this scientific practice has been also considered in the approaches based on inquiry. To justify this, Crawford refers to the research done by the renowned expert Abell and her co-workers, who already put argumentation at the center of their approaches to learning and teaching science through inquiry a decade before the current standards were published (ibid., pp. 523–524).

In addition to Abell and co-workers, I find in the literature other authors who also gave special importance to argumentation in their approaches for science learning as inquiry, before the publication of the NGSS Lead States (2013) (e.g., Jiménez-Aleixandre et al. 2000; Kim and Song 2006; Reiser et al. 2001; Sampson and Gleim 2009; Sampson et al. 2009; Tang et al. 2010). For instance, Reiser et al. (2001) referred to argumentation in the BGuILE project as follows:

> In our designs, we explore an approach that tries to make the relationship between argumentation goals, domain theories and investigation strategies explicit for students. There are two types of relationships we need to support for students. The first is the connection between the argumentation goals and investigation strategies. In learning and practicing a strategy, students need to see how that strategy affects the type of inquiry product they produce (…) (p. 270).

In the Spanish context, some well-known school projects for science learning through inquiry in primary education also promoted argumentation 15 years ago. For example, the "Inquiring our World (6-12)" project (Cañal et al. 2005) established among its main learning goals to acquire capacities for *engaging in process of debate of ideas through dialog*, *argumentation*, *negotiation*, *and decision-making*.

Likewise, the European Fibonacci Project (2010–2013), which was framed in inquiry-based learning, and whose committee includes Harlen, also referred to argument in school science. For example, one of the basic objectives of this educational project was to "Help students to understand that evidence and scientific reasoning determine the conclusions, not the number of proponents for a given opinion or the arguments of the strongest students" (Harlen 2012, p. 15).

Regarding *modeling*, before the NGSS Lead States (2013), didactic proposals were already being made about modeling in contexts of learning through inquiry. In the late 1990s, for example, the US researchers Barbara Y. White and John R. Frederiksen presented the results of

Table 1 Comparing inquiry in National Science Education Standards (NSES) (NRC 1996, 2000) and practices in the K–12 Framework (NRC 2012) (taken from Crawford 2014, p. 523)

NSES (NRC 1996, 2000) Essential features of inquiry	K–12 Framework (NRC 2012) Science and engineering practices
Learners are engaged by scientifically oriented questions	Asking questions (for science) and defining problems (for engineering)
Learners give priority to evidence, which allows them to develop and evaluate explanations that address scientifically oriented questions	Developing and using models Planning and carrying out investigations Analyzing and interpreting data
Learners evaluate their explanations in light of alternative explanations, particularly those reflecting scientific understanding	Using mathematics and computational thinking
Learners communicate and justify their proposed explanations	Constructing explanations (for science) and designing solutions (for engineering) Engaging in argument from evidence Obtaining, evaluating, and communicating information

a much-cited study[7] which analyzed the effectiveness of a proposal to learn mechanics through cycles of inquiry, in which modeling explicitly formed a part:

> (…) into an Inquiry Cycle that is explicitly presented to students (…) [they] pursue a sequence of research goals in which they first formulate a question and then generate a set of competing predictions and hypotheses related to that question. In order to determine which of their competing hypotheses is accurate, they then plan and carry out experiments (…). Next, they analyze their data and summarize their findings in the form of scientific laws and models. Finally, they apply their laws and models to various situations. (…) It engages middle school students in authentic scientific inquiry in which their primary goal is to create and apply causal models of force and motion. (…) the purpose is to enable students to learn about the process of scientific inquiry and modeling while at the same time learning about the physics of force and motion (White and Frederiksen 1998, pp. 4–5; the brackets are mine).

Abell and co-workers also included the development of models among the objectives of their teacher training plans for teaching science as inquiry; for example, the construction of models of light, electric current, and resistance in an inquiry focused on the study *how to light a bulb* by means of an elemental electric circuit (Abell et al. 2006), or the development of models of the Moon and the Earth-Moon-Sun system in an inquiry about the Moon's phases (Volkmann and Abell 2003). Likewise, prior to the latest standards, there had emerged educational proposals for learning science by inquiry which explicitly included modeling, using terms of the type "model-based inquiry" (Windschitl et al. 2008). At this respect, I also think it is necessary to point out that carrying out inquiry and modeling practices is not the same as model-based inquiry. The former would refer to carrying out two different scientific practices of equal epistemological status and integrated into the context of a particular school science activity. However, the latter would refer to a specific acceptance or conceptualization of inquiry in which the generating, testing, and revising of scientific models receive a special attention (Nuffield Foundation 2013). Something similar can be said for argumentation and "argument-driven inquiry" (Sampson et al. 2009).

[7] According to Google Scholar, this article currently has close to 1900 citations.

Crawford (2014) highlights another distinctive characteristic of the framework of scientific practices proposed by NGSS Lead States (2013): the emphasis that learning about science (and engineering) involves the integration of content knowledge and the practices necessary to participate in an inquiry. However, I think it is opportune to note two considerations in this regard.

Firstly, the need to integrate or handle scientific knowledge in order to participate in practices is an idea that was already present in the standards prior to the development of the inquiry-based approach (NRC, 1996, p. 2): "When engaging in inquiry, students (…) actively develop their understanding of science by combining scientific knowledge with reasoning and thinking skills." Bybee (2011) also points out that: "During the period 1960–1990, interest and support grew for scientific inquiry as an approach to science teaching that emphasized learning science concepts and using the skills and abilities of inquiry to learn those concepts" (p. 14). Attention to scientific knowledge is also very clearly present in Harlen's approach to science learning as inquiry: "Inquiry-based science education means students progressively developing their knowledge and understanding of the world around through their own mental and physical activity" (Harlen 2012, p.22).

Secondly, in NGSS, it seems to be insinuated that learning about science (i.e., understanding of nature of science [NOS]) can be acquired solely by participating in scientific practices. However, what education research has repeatedly shown is that NOS is usually only effectively comprehended through explicit reflective approaches (Lederman 2007, 2019; Clough 2018), i.e., through an approach that conceives NOS as specific curricular content with its own learning objectives, whose development in science class requires the design of activities aimed at getting the students to think and discuss reflectively about NOS questions, and appropriate evaluation strategies.

Previous standards (NRC, 1996, 2000) did distinguish between understanding scientific inquiry (i.e., understanding of nature of scientific inquiry) and the capacities needed to do scientific inquiries (Bybee 2006). A very different issue is that this differentiation of learning objectives that was promoted in the old standards seems not to have been adequately projected in the teaching proposals that were actually implemented in science classes (Lederman 2019).

In order to deepen in the latter, it seems opportune to analyze that nature of the two constructs may help, taking into account the prevailing educational traditions and the alternatives that are being put forward. I shall address this issue in the following section.

4 Nature of the Inquiry and Scientific Practice Constructs

In the context of inquiry-based science education, the conceptualization of the characteristic features of the work that scientists do (i.e., nature of scientific inquiry) was approached through what were called *understandings about scientific inquiry* (Bybee 2006). The basic ideas of these are given in Table 2. One observes that such understandings about nature of scientific inquiry are biased towards epistemic aspects, i.e., they are practically limited to cognitive or rational aspects of science. However, any conceptualization of scientific inquiry which does not consider aspects of a sociological nature (or *non-epistemic aspects*), which also intervene in (or are part of) the usual scientific practices of persons dedicated to science, is quite limited, as the history and sociology of science show (Acevedo-Díaz et al. 2017; Allchin 2004; Collins 2015; Dagher and Erduran 2016; Knorr-Cetina 1981; Matthews 2012). Is the

Table 2 Understandings about scientific inquiry (taken from Bybee 2006, p. 4)

Different kinds of questions suggest different kinds of scientific investigations
Current scientific knowledge and understanding guide scientific investigations
Mathematics is important in all aspects of scientific inquiry
Technology used to gather data enhances accuracy and allows scientists to analyze and quantify investigation results
Scientific explanations emphasize evidence, have logically consistent arguments, and use scientific principles, models, and theories
Science advances through legitimate skepticism
Scientific investigations sometimes result in new ideas and phenomena for study, generate new methods or procedures for investigation, or develop new techniques to improve the collection of data

constant search for funds to do research, the struggle with the scientific establishment to put forward new scientific ideas, cooperation, competitiveness, and professional ethics, to mention just a few examples, not also part of scientists' usual practice? In a review of the book of the sociologist Knorr-Cetina (1981), "The Manufacture of Knowledge," Pablo Kreimer (2005) wrote:

> (…) the first thing researchers have to do when defining an investigation line is to find a resource of funding which allows them to buy equipment, to recruit assistants, etc. Usually, funding agencies do not finance any type of investigation, but that they have priorities, methodologies, privileged orientations, etc. Thus, researchers must negotiate with the agencies the provision of resources which are necessary for their projects. Therefore, there is no reason to suppose that the nature of these relationships, which are clearly "extra-scientific", is something that is "out of" the manufacture of knowledge, but that on the contrary this determines it strongly (p. 213; the translation is mine).

In the NGSS Lead States (2013), there is no specific proposal about understanding of scientific practices. Therefore, it is necessary to search these within the categories related to understandings about NOS, which are distributed proportionally among cross-cutting concepts and the scientific practice dimensions. Such categories are (Appendix H, NGSS Lead States, 2013, p. 4) the following: (1) Scientific investigations use a variety of methods; (2) Scientific knowledge is based on empirical evidence; (3) Scientific knowledge is open to revision in light of new evidence; (4) Scientific models, laws, mechanisms, and theories explain natural phenomena; (5) Science is a way of knowing; (6) Scientific knowledge assumes an order and consistency in natural systems; (7) Science is a human endeavor; and (8) Science addresses questions about the natural and material world.

Appendix H further develops these categories of understandings in a progressive manner for three educational levels—primary, lower secondary, and upper secondary. It should be noted that these include aspects of both nature of scientific knowledge[8] and nature of scientific practices. Here, I shall focus on those categories which, in my opinion, are related to the work that scientists do and/or to factors that influence that work. The categories selected are listed in Table 3, exemplified for the lower secondary case (middle school). I have highlighted in boldface those characteristics of each of the categories which, from my point of view, would be most specifically related to the work of scientists.

On analyzing the conceptualization of the scientific practice construct that one infers from the NGSS, i.e., the features that characterize scientists' work (Table 3), it can be said that there

[8] In the different documents concerning the reform of science education in the USA prior to the NGSS Lead States (2013), nature of science was identified with nature of scientific knowledge (Lederman 2019).

is still a clear lack of attention being paid to the sociological perspective of scientific practices. I only found a few aspects worthy of note compared with what was included in the "understandings about scientific inquiry" of the previous standards (Table 2). Indeed, they constitute just a fairly small proportion of the total features. One example is the explicit mention that both men and women work in science, and that many people from different generations and countries have contributed to elaborating the knowledge of science. These aspects, however, were also mentioned in previous standards (NRC 1996), although within the "History and Nature of Science Standards" section, itself part of the science content standards. Therefore, neither do these really represent anything novel.

In the literature, it can be found some interesting theoretical positions about scientific practices and science education, such as those of Gregory J. Kelly. He identifies scientific practices with "epistemic practices" and conceives them as "the specific ways members of a community propose, justify, evaluate, and legitimize knowledge claims within a disciplinary framework" (Kelly 2008, p. 99). Thus, for Kelly and co-workers, social practices are considered patterned actions which are recognizable among members of the (scientific) community (Kelly and Licona 2018, p. 6). Therefore, "practices are learned through participation and often entail extended interactions with members already familiar with the ways that practices are recognized as socially significant" (ibid., p. 6). From this perspective, in which science is seen as a process of social construction, Kelly (2008) argues that research on inquiry-based science teaching needs to examine learning situated in sociocultural practices (p. 104).

While the Kelly's approach on scientific practices seems to me very coherent and suggestive, I do not share some details thereof. Firstly, if Kelly assumes that the social dimension has a relevant role in the development of science, why does he choose to call scientific practices "epistemic practices?" In my opinion, this denomination does not adequately represent the discourse behind Kelly's position because "epistemic" is an adjective commonly associated to rational or cognitive aspects in the construction of scientific knowledge.[9] For example, in the Irzik and Nola's (2014) conceptualization of NOS, in which nature of scientific practices is included, *cognitive-epistemic* factors are distinguished from *social-institutional* ones.[10] The former refers to processes of inquiry, aims and values (prediction, explanation, consistency, simplicity, and fruitfulness), methods and methodological rules, and scientific knowledge; while, the latter includes professional activities, scientific ethos, certification and dissemination of scientific knowledge, and social values (ibid.). In a similar vein, Stroupe (2014, 2015) considers four dimensions of disciplinary work in his approach for learning *science as practice*,[11] among which the epistemic dimension is explicitly differentiated from the social one. The social dimension focused on "how actors agree on norms and routines for handling, developing, critiquing, and using ideas" (Stroupe 2015, p. 1034), and the epistemic dimension is defined as "the philosophical basis by which actors decide what they know and why they are convinced they know it" (ibid.).

Secondly, that denomination leads me to interpret that Kelly ultimately conceives the social (or non-epistemic) practices as subordinated to the epistemic practices. In other words, the social practices would only be an "ingredient" in the configuration or development of

[9] The adjective "epistemic" derives from the Greek term episteme whose meaning in its philosophical acceptance is "knowledge that is methodologically and rationally constructed as against opinions which lack foundation" (Spanish Royal Academy's Dictionary, https://www.rae.es).

[10] A similar perspective is also assumed by other authors in their approaches for NOS/nature of scientific practices (e.g., García-Carmona and Acevedo-Díaz 2018; Erduran et al. 2019; Martins 2015).

[11] The four dimensions are *conceptual, social*, *epistemic*, and *material* (Stroupe 2014, 2015).

Table 3 Understandings about the nature of science for middle school regarding those categories more focused on what scientists do (elaborated from NGSS Lead States, 2013, Appendix H, pp. 5–6)

Categories	Characteristic features*
Scientific investigations use a variety of methods	**Science investigations use a variety of methods and tools to make measurements and observations** **Science investigations are guided by a set of values to ensure accuracy of measurements, observations, and objectivity of findings** **Science depends on evaluating proposed explanations** Scientific values function as criteria in distinguishing between science and non-science
Scientific knowledge is open to revision in light of new evidence	**Scientific explanations are subject to revision and improvement in light of new evidence** The certainty and durability of science findings vary **Science findings are frequently revised and/or reinterpreted based on new evidence**
Science models, laws, mechanisms, and theories explain natural phenomena	Theories are explanations for observable phenomena Science theories are based on a body of evidence developed over time Laws are regularities or mathematical descriptions of natural phenomena **A hypothesis is used by scientists as an idea that may contribute important new knowledge for the evaluation of a scientific theory** The term "theory" as used in science is very different from the common use outside of science
Science is a way of knowing	Science is both a body of knowledge and the processes and practices used to add to that body of knowledge Science knowledge is cumulative and **many people, from many generations and nations, have contributed to science knowledge** Science is a way of knowing used by many people, not just scientists
Science is a human endeavor	**Men and women from different social, cultural, and ethnic backgrounds work as scientists and engineers** **Scientists and engineers rely on human qualities such as persistence, precision, reasoning, logic, imagination, and creativity** **Scientists and engineers are guided by habits of mind such as intellectual honesty, tolerance of ambiguity, skepticism, and openness to new ideas** Advances in technology influence the progress of science, and science has influenced advances in technology

*The underlining is mine

epistemic practices, which are the truly important thing.[12] However, as Elliott and McKaughan (2014) have shown, "non-epistemic values can legitimately influence the assessment of scientific representations for practical purposes not only as secondary considerations in situations of uncertainty but also as factors that can take priority over epistemic values" (p. 18). In effect, history of science shows that many times, the non-epistemic factors have played a role at least as important as the epistemic ones in the legitimization or delegitimization of

[12] I would not possibly interpret it in this way if Kelly always was talking about "scientific practices" in his theoretical approach. I think that language is very important in any knowledge area, and the selection of a name is always intentional—one is seeking a precise as possible designation of the idea one wants to represent.

scientific knowledge. For instance, the difficulties and low interest of Ignaz Semmelweis in scientific communication or his bad personal relationships with his medical colleagues, in addition to other causes epistemic in nature, affected notably that his scientific ideas about childbed fever were not recognized by scientific community in his time (Aragón-Méndez et al. 2019). Likewise, Louis Pasteur's rhetorical and semantic skills, together with other epistemic details, were essential to impose his ideas on those of Justus von Liebig regarding the fermentation, although Pasteur neither achieved to explain this phenomenon scientifically (García-Carmona and Acevedo-Díaz 2017). It could also be pointed out the unethical or illegal practices followed by scientists in the building of scientific knowledge. At this respect, Swain (2019) recently wrote that "there are few corners of scientific progress that are not tainted at some point in their history by immoral or unethical behaviour." And, he then referred, among other examples, to the following:

> From 1955 to 1976, in what became known as "The Unfortunate Experiment", hundreds of women with pre-cancerous lesions were left untreated to see if they developed cervical cancer. Details of the study only came to light following an expose by two women's health advocates Sandra Coney and Phillida Bunkle. The New Zealand study hoped to test theories about the value of early intervention (…) (ibid.).

Jiménez-Aleixandre and Crujeiras (2017) note that sometimes "epistemic practices" and "scientific practices" are used as terms interchangeably in the literature. They however think that, from a rigorous view, the two terms should be treated as different. But even so, they consider that any overlapping exists between them particularly in the educational context. Jiménez-Aleixandre and Crujeiras then add: "we suggest that we can think of epistemic practice as a broader construct and of scientific practices as epistemic practices in the context of specific learning contexts or content areas" (ibid., p. 70). However, they do not justify the epistemological or hierarchical relationship which they propose between scientific practices and epistemic practices. In my view, scientific practices comprise both *epistemic tasks* (e.g., to formulate hypotheses, to develop models, to perform scientific measurements, to select and apply analysis methods, to interpret empirical data, and to handle mathematical tools), and *non-epistemic tasks* (e.g., to collaborate and cooperate with scientific colleagues, to communicate research findings, to know and assume ethical commitments in research, and to search for economic support to do research) (García-Carmona and Acevedo-Díaz 2018). Therefore, from this perspective, "scientific practices" would be a broader construct than "epistemic practices."

Duschl (2008) is more explicit in considering both epistemic and social practices in an integrated way in his approach for science education. Furthermore, he considers both types of practices at the same level of educational significance.[13] Particularly, Duschl (2008) suggests that the incorporation and assessment of science learning in educational contexts should focus on three integrated domains (p. 277): (a) the *conceptual* structures and *cognitive* processes used when reasoning scientifically, (b) the *epistemic* frameworks used when developing and evaluating scientific knowledge, and (c) the *social* processes and contexts that shape how knowledge is communicated, represented, argued, and debated.[14] I also think it is very important to highlight, as Duschl does, that these three domains should be subject of

[13] Duschl (2008) specifically talks about "a more balanced focus among things conceptual, epistemic, and social" (p. 283).

[14] For Kelly (2014), striving to meet these three objectives of science education demands a critical analysis and discussions about nature of inquiry, which I fully share with him. I consider this is independent of my critique on his terminology usage regarding "practices," which I exposed above.

assessment in science learning, because educators do not usually teach what does not have to be assessed. However, as earlier noted, this approach in which epistemic and non-epistemic practices are explicitly distinguished, but integrated, and taken on with equal importance for science education is not clearly developed in NGSS Lead States (2013) nor in the majority of the educational proposals aligned whit them.

5 Conclusion

After this particular analysis from both research literature and various curricular documents/reports for science education, my conclusion is that learning science based on engaging in scientific practices, as suggested in the influential NGSS Lead States (2013), differs substantially little from the inquiry-based science learning approach. I have verified that practically all that is proposed for practice-based science learning in such document, and in the research literature related to this, were already included, in any way, in the more genuine approaches for inquiry-based science education (e.g., Abell et al. 2006; Harlen 2012; Reiser et al. 2001; White and Frederiksen 1998). In addition, the majority of scientific practices for science education, which are proposed in NGSS, are identified as science inquiry skills (or similar terms) in the current science curricula of countries such as Australia (ACARA 2015), Canada (Ministry of Education 2008), Israel (Mullis et al. 2016), and UK (Department for Education 2013), among others.

Likewise, from the perspective of which elements of scientific practices are conceived of as being representative or characteristic of the activity of scientists, I find no significant change in NGSS Lead States (2013) with relation to the construct of nature of scientific inquiry that had been promoted before (Bybee 2006). Both constructs are characterized in the corresponding standards by epistemic features almost exclusively. By this, I do not mean that it seems to me inadequate, but rather incomplete. According to Collins (2015), the neglect of the sociological perspective of scientific practice implies teaching a "diluted" version of science. From this same view, Mody (2015) describes scientific practice as being messy, contradictory, and more reasonable than rational (p. 1026), and thus, he suggests that practice-based science education should emphasize that "other" forms of knowledge also form an essential part of science (p. 1030). I fully agree with these authors' view and I therefore consider that it would have been more significant to promote a wider conception of scientific practices that integrates both their epistemic and their sociological (or non-epistemic) dimensions in an explicit, balanced, and harmonized manner (García-Carmona and Acevedo-Díaz 2018). That would basically be favoring a form of science education more in line with real scientific practice. However, I believe that, with the presentation of influential documents such as K–12 Framework and NGSS, an opportunity has been missed to propose a didactic framework for scientific practices of broader scope and perspective, with a view to overcome the limitations detected in usual implementations of the inquiry-based approach in science classes.

In summary, I do not consider that going from a framework based on inquiry to one based on scientific practices can be reduced to a simple change of terminology. However, according to everything that was analyzed here, I find there to be sufficient reasons for science educators, to whom these proposals are addressed, to question that the newly proposed approach is really different or innovative, as mentioned above (see, for example, Furtak and Penuel 2019). Indeed, even some renowned authors have come to describe scientific practices simply as "the new term" for inquiry (see, for instance, Lederman and Lederman 2014, p. 236). In a similar vein, Harlen (2015) considers scientific practices as an equivalent term to science inquiry capabilities/skills (pp. 11, 12, 46).

Likewise, the recent report of the European Schoolnet network (Durando et al. 2019) on teacher training in the inquiry-based approach to science learning refers to scientific practices as only being an "alternative term to 'inquiry'. It makes explicit that 'doing science' is a process with many components" (p. 8). Even so, I think the practice-based approach could be the *enhanced version* of that based on inquiry, and therefore to represent a completer and holistic image of science, if—as it has been said—non-epistemic practices are also tackled. In the following and final section, I will do some suggestion at this respect.

Finally, I would like to point out that I have intended to do a rigorous, yet not systematic, review of relevant literature related to the question addressed. The analysis presented is critical and reflective in nature that emerges from my concern as a science teacher educator in the presence of a new approach to teach science, which, in my opinion, is not sufficiently justified or not adequately articulated. I have therefore sought arguments that can support my skeptical perception. In this sense, I am aware that this analysis is only one among other possible, and it therefore presents the characteristic limitations of this type of analyses. Consequently, my main purpose has been to contribute with a particular, critical, and constructive viewpoint regarding the change from inquiry to scientific practices in science education, which is being currently promoted from one part of the science education community.

6 Implications for science teaching based on scientific practices

The critical-reflective analysis presented here will only make sense if it is followed by being echoed in the school science curricula and, consequently, in science classes where it has to be developed. Thus, the next step should be to determine which aspects of scientific practices would be the most appropriate or viable for each educational level, and, in particular, how to transpose them didactically to be suitable for real science classes. I think that there are good examples in the recent literature for the implementation of these approaches in class, even though these examples predominantly take an epistemic perspective on scientific practices (e.g., Berland et al. 2016; Zangori and Forbes 2014). Therefore, there is a need to promote educational proposals that, while integrated with the practices of an epistemic profile, also have a focus on practices of a non-epistemic (or social) nature, adapted appropriately to the school context.

For instance, it would be interesting to promote and normalize among students the establishment of ethical codes that commit them to rigor and honesty in the collection of empirical data, as well as to adopt appropriate standards and behavior in inquiries involving living beings (plants, snails, silkworms, etc.) and other elements of natural spaces (interacting with them without altering them). In validating the conclusions of their inquiries, the students could also combine their evaluation with "anonymous" peers (double blind) and with "known" peers, in order to contrast and reflect upon the two processes. The aim of this would be students are aware that it is useful in order to avoid possible prejudices and/or conflicts of interest in the evaluation of their results, as well as to enrich that evaluation with the argued critique of more than one evaluator, etc. Also, in analogy with scientists' search for funds to support their research, it would be good to encourage students to think about how to conduct scientific inquiries at the lowest possible cost, thus favoring the development of capacities for planning, organizing, and managing resources in the school laboratory, and encouraging their awareness of the recycling and reusing of materials. These and other examples of learning standards associated with non-epistemic scientific practices are shown in Table 4. This proposal should be seen as one possible among others, in addition to expandable. Likewise, these learning standards would have to be adequately adjusted depending of each educational context and content of science curriculum, and progressively developed along the different school levels.

Finally, in order to illustrate how epistemic and non-epistemic practices could be integrated in a same learning context, an inquiry activity is presented as an example in Fig. 1. This activity was originally designed for addressing only epistemic tasks in the study of a thermal phenomenon (García-Carmona 2020), which connects with learning standards established in the "Scientific activity" and "Energy" content blocks

Table 4 A possible proposal of learning standards associated to non-epistemic scientific practices

Non-epistemic scientific practices	Learning standards
Social perspective of scientific communication	Students collectively determine format and content standards of scientific inquiry reports
	Students collectively establish standards to communicate and debate in whole class sessions the different inquiry findings
	Students organize themselves to boost and moderate discussions on the different inquiry findings in whole class sessions, and to record global conclusions
Professional and personal relationships among scientists/gender in scientific investigation	Students organize the tasks and assign roles to the different members of a work team during scientific inquiries
	Students are organized into work teams so that these include boys and girls in balanced proportions, and the different roles of the members of a work team are assigned regardless of gender
Role of scientific community in the acceptance of scientific theories (intersubjectivity)	Within a work team, students establish criteria to decide how to discuss and elaborate scientific explanations and/or arguments, which are representative of the work team
	Students collectively establish criteria (e.g., rubrics) and processes (e.g., "anonymous" peers and "known" peers) to evaluate the inquiry findings presented by work teams
Scientists' rhetorical skills and semantic strategies to persuade through own ideas	Students make a maximum effort to write well their inquiry reports and communicate them well orally in order to convince others through own ideas or conclusions
Scientific collaboration and cooperation	Students elaborate standards of cooperation and collaboration among work teams when participating in scientific inquiries (e.g., exchange of ideas or inquiry strategies and offering of help to those with greater difficulties to advance)
Moral and ethical issues in scientific investigation	Students value and discuss critically the scientific and/or social interest of inquiry questions from ethical, moral, political, economic, etc. criteria
	Students plan scientific inquiries that are environment-friendly
	Students collectively establish appropriate behavior standards in scientific inquiries involving living beings and other elements of natural spaces
	Students elaborate ethical standards to follow in collection and analysis of data (honesty in the collection of empirical data, rigor criteria in analyzing them, etc.)
Seeking funds for scientific investigation	Students plan scientific inquiries bearing in mind the available budget (preferably of low cost), including the possibility of recycling or reutilizing materials

THE PROBLEM FOR INQUIRY

Some friends get together to organize a birthday party. It's summer, and they plan to have a refreshing drink, but they're not sure what type of glass or cup to use to make the drink stay cool longer while they are drinking it. They discuss whether to use plastic, stainless steel, ceramic, or glass, but no one is convinced about which would be the best option. If you were one of them, what would your proposal be and why?

LEARNING GOALS

- To observe, analyze and describe the thermal properties of some materials of everyday use.
- To classify materials in thermal conductors or insulators according to their thermal conductivities and specific heat capacities.
- To understand the difference between the concepts of heat and temperature.
- To plan and tackle a scientific inquiry on a thermal phenomenon, communicating the process followed and the result obtained.
- To establish rules for organization of work, commitments to participation and ethical standards in planning and conducting the scientific inquiry, as well as in communicating and discussing the results and conclusions obtained.

SCRIPT FOR PLANNING, DEVELOPING AND EVALUATING THE INQUIRY

Design and planning

Epistemic tasks	*Non-epistemic tasks*
- *Establish a hypothesis:* Try to advance a possible solution or response to the question, attempting to base it on the scientific knowledge you have about the phenomenon. - *Plan the experiment:* Think about and explain what procedure you are going to follow to check the validity of your hypothesis.	- Discuss and decide what criteria of "good practices" (or ethical criteria) you will commit within the work team regarding the: (a) handling of laboratory materials, and (b) data collection and its analysis. - Decide how will you organize yourself within the work team in order to plain and conduct the different tasks of inquiry.
- *Observe the phenomenon and record data:* Explain what data you will take and how you will process it.	- Establish what personal commitments each of you should be acquire within the work team, in order to this inquiry activity can be finished successfully.

Evaluation of results and conclusions

Epistemic tasks	*Non-epistemic tasks*
- *Scientific interpretation of the results:* Explain whether the results obtained are coherent with what science establishes respecting the phenomenon analyzed. - *Verify the hypothesis:* In view of the results obtained and their scientific interpretation, determine whether or not your hypothesis is valid. - *Detect the limitations of the inquiry:* Indicate what errors, limitations, or difficulties (conceptual and/or procedural) you think you had during the inquiry.	- Establish what criteria you will use within the work team in order to decide how to draw conclusions, which represent the team in the discussion of findings with other teams. - Decide in a consensual manner with other work teams the criteria and processes that will be followed in evaluating the different findings from inquiry. - Discuss and decide by consensus among work teams (a) the format (structure, esthetic, etc.) and content of inquiry report, which each team has to elaborate, and (b) the rules for communicating and debating the different findings and conclusions in class.

Fig. 1 Inquiry activity that integrates both epistemic and non-epistemic tasks in the same learning context related to a thermal phenomenon (adapted and expanding from García-Carmona 2020)

corresponding to the Spanish secondary science curriculum (Education Ministry 2015). However, the activity is now expanded by also including some non-epistemic tasks that could be tackled along with the epistemic ones.

Funding Information This study was supported by the Ministry of Economy, Industry and Competitiveness (Government of Spain) under grant EDU2017-82505-P.

Compliance with Ethical Standards

Conflict of Interest The author declared that he has no conflicts of interest.

References

Abd-El-Khalick, F., Boujaoude, S., Duschl, R., Lederman, N. G., Mamlok-Naaman, R., Hofstein, A., et al. (2004). Inquiry in science education: International perspectives. *Science Education, 88*(3), 397–419.

Abell, S. K., Smith, D. C., & Volkmann, M. J. (2006). Inquiry in science teacher education. In L. B. Flick & N. G. Lederman (Eds.), *Scientific inquiry and nature of science* (pp. 173–199). Dordrecht: Springer.

Acevedo-Díaz, J. A., García-Carmona, A., & Aragón, M. M. (2017). *Enseñar y aprender sobre naturaleza de la ciencia mediante el análisis de controversias de historia de la ciencia. Resultados y conclusiones de un proyecto de investigación didáctica* [Teaching and learning about nature of science through the analysis of controversies from history of science. Results and conclusions of an educational research project]. Madrid: Organización de Estados Iberoamericanos para la Educación, la Ciencia y la Cultura (OEI).

Allchin, D. (2004). Should the sociology of science be rated X? *Science Education, 88*(6), 934–946.

Anderson, R. D. (2002). Reforming science teaching: What research says about inquiry. *Journal of Science Teacher Education, 13*(1), 1–12.

Aragón-Méndez, M. M., Acevedo-Díaz, J. A., & García-Carmona, A. (2019). Prospective biology teachers' understanding of the nature of science through an analysis of the historical case of Semmelweis and childbed fever. *Cultural Studies of Science Education, 14*(3), 525–555.

Arnold, J. C., Kremer, K., & Mayer, J. (2014). Understanding students' experiments—What kind of support do they need in inquiry tasks? *International Journal of Science Education, 36*(16), 2719–2749.

Asay, L. D., & Orgill, M. (2010). Analysis of essential features of inquiry found in articles published in The Science Teacher, 1998–2007. *Journal of Science Teacher Education, 21*(1), 57–79.

Australian Curriculum, Assessment and Reporting Authority [ACARA]. (2015). *Foundation–Year 10 Australian Curriculum: Science*. Retrieved from: https://www.australiancurriculum.edu.au/f-10-curriculum/science/. Accessed 30 Jan 2020.

Barrow, L. H. (2006). A brief history of inquiry: From Dewey to standards. *Journal of Science Teacher Education, 17*, 265–278.

Berland, L. K., Schwarz, C. V., Krist, C., Kenyon, L., Lo, A. S., & Reiser, B. J. (2016). Epistemologies in practice: Making scientific practices meaningful for students. *Journal of Research in Science Teaching, 53*(7), 1082–1112.

Bevins, S., & Price, G. (2016). Reconceptualising inquiry in science education. *International Journal of Science Education, 38*(1), 17–29.

Bybee, R. W. (2006). Scientific inquiry and science teaching. In L. B. Flick & N. G. Lederman (Eds.), *Scientific inquiry and nature of science* (pp. 1–14). Dordrecht: Springer.

Bybee, R. W. (2011). Scientific and engineering practices in K-12 classrooms: Understanding a framework for K-12 science education. *Science and Children, 49*(4), 10–16.

Cañal, P., Pozuelos, F. J., & Travé, G. (2005). *Proyecto Curricular Investigando Nuestro Mundo (6-12). Descripción General y Fundamentos [The "Inquiring our World (6-12)" Project. General Description and Foundations]*. Sevilla: Díada.

Cheng, M. F., Wu, T. Y., & Lin, S. F. (2019). Investigating the relationship between views of scientific models and modeling practice. *Research in Science Education*, 1–17. https://doi.org/10.1007/s11165-019-09880-2

Clough, M. P. (2018). Teaching and learning about the nature of science. *Science & Education, 27*(1–2), 1–5.

Collins, H. (2015). Can we teach people what science is really like? *Science Education, 99*(6), 1049–1054.

Crawford, B. A. (2000). Embracing the essence of inquiry: New roles for science teachers. *Journal of Research in Science Teaching, 37*(9), 916–937.

Crawford, B. A. (2007). Learning to teach science as inquiry in the rough and tumble of practice. *Journal of Research in Science Teaching, 44*(4), 613–642.

Crawford, B. A. (2014). From inquiry to scientific practices in the science classroom. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of research on science education, volume II* (pp. 515–541). New York: Routledge.

Crujeiras-Pérez, B., & Jiménez-Aleixandre, M. P. (2018). *Influencia de distintas estrategias de andamiaje para promover la participación del alumnado de secundaria en las prácticas científicas* [Influence of different scaffolding strategies for engaging secondary students in scientific practices]. *Enseñanza de las Ciencias, 36*(2), 23–42.

Dagher, Z. R., & Erduran, S. (2016). Reconceptualizing the nature of science for science education. Why does it matter? *Science & Education, 25*(1–2), 147–164.

Department for Education. (2013). Science programmes of study: Key stages 1 and 2. National curriculum in England: Science programmes of study.

Durando, M., Sjøberg, S., Gras-Velazquez, A., Leontaraki, I., Martin Santolaya, E., & Tasiopoulou, E. (2019). *Teacher training and IBSE practice in Europe–A European Schoolnet overview*. Brussels: European Schoolnet.

Duschl, R. (2008). Science education in three-part harmony: Balancing conceptual, epistemic and social learning goals. *Review of Research in Education, 32*, 268–291.

Education Ministry. (2014). *Royal Decree 126/2014, February 28, establishing the basic curriculum of primary education*. Madrid: Official Bulletin of the State.

Education Ministry. (2015). *Royal Decree 1105/2014, January 3, establishing the basic curriculum of secondary education*. Madrid: Official Bulletin of the State.

Elliott, K. C., & McKaughan, D. J. (2014). Nonepistemic values and the multiple goals of science. *Philosophy of Science, 81*(1), 1–21.

Erduran, S. (2015). Introduction to the focus on… scientific practices. *Science Education, 99*(6), 1023–1025.

Erduran, S., Dagher, Z. R., & McDonald, C. V. (2019). Contributions of the family resemblance approach to nature of science in science education. *Science & Education, 28*(3–5), 311–328.

Ford, M. (2008). Disciplinary authority and accountability in scientific practice and learning. *Science Education, 92*(3), 404–423.

Ford, M. J. (2015). Educational implications of choosing "practice" to describe science in the next generation science standards. *Science Education, 99*(6), 1041–1048.

Forman, E. A., & Ford, M. J. (2014). Authority and accountability in light of disciplinary practices in science. *International Journal of Educational Research, 64*, 199–210.

Furtak, E. M., & Penuel, W. R. (2019). Coming to terms: Addressing the persistence of "hands-on" and other reform terminology in the era of science as practice. *Science Education, 103*(1), 167–186.

Furtak, E. M., Shavelson, R. J., Shemwell, J. T., & Figueroa, M. (2012). To teach or not to teach through inquiry. In J. Shrager & S. Carver (Eds.), *The journey from child to scientist: Integrating cognitive development and the education sciences* (pp. 227–244). Washington, DC: American Psychological Association.

García-Carmona, A. (2020). Prospective elementary teachers' abilities in tackling a contextualized physics problem as guided inquiry. *Revista Brasileira de Ensino de Física, 42*, e20190280. https://doi.org/10.1590/1806-9126-RBEF-2019-0280.

García-Carmona, A., & Acevedo-Díaz, J. A. (2017). Understanding the nature of science through a critical and reflective analysis of the controversy between Pasteur and Liebig on fermentation. *Science & Education, 26*(1), 65–91.

García-Carmona, A., & Acevedo-Díaz, J. A. (2018). The nature of scientific practice and science education. *Science & Education, 27*(5–6), 435–455.

García-Carmona, A., Criado, A. M., & Cruz-Guzmán, M. (2017). Primary pre-service teachers' skills in planning a guided scientific inquiry. *Research in Science Education, 47*(5), 989–1010.

García-Carmona, A., Criado, A. M., & Cruz-Guzmán, M. (2018). Prospective primary teachers' prior experiences, conceptions, and pedagogical valuations of experimental activities in science education. *International Journal of Science and Mathematics Education, 16*(2), 237–253.

Harlen, W. (2012). *Fibonacci project. Background resources for implementing inquiry in science and mathematics at school*. Paris: Fondation La main à la pâte.

Harlen, W. (Ed.). (2015). *Working with big ideas of science education*. Trieste: Science Education Programme of IAP.

Hmelo-Silver, C. E., Duncan, R. G., & Chinn, C. A. (2007). Scaffolding and achievement in problem-based and inquiry learning: A response to Kirschner, Sweller, and Clark (2006). *Educational Psychologist, 42*(2), 99–107.

Hodson, D. (2014). Learning science, learning about science, doing science: Different goals demand different learning methods. *International Journal of Science Education, 36*(15), 2534–2553.

Irzik, G., & Nola, R. (2014). New directions for nature of science research. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 999–1021). Dordrecht: Springer.

Jiménez-Aleixandre, M. P., & Crujeiras, B. (2017). Epistemic practices and scientific practices in science education. In K. S. Taber & B. Akpan (Eds.), *Science education* (pp. 69–80). Rotterdam: Sense.

Jiménez-Aleixandre, M. P., Bugallo Rodríguez, A., & Duschl, R. A. (2000). "Doing the lesson" or "doing science": Argument in high school genetics. *Science Education, 84*(6), 757–792.

Jiménez-Liso, M. R., Martínez-Chico, M., Avraamidou, L., & López-Gay, R. (2019). Scientific practices in teacher education: The interplay of sense, sensors, and emotions. *Research in Science & Technological Education*, 1–24. https://doi.org/10.1080/02635143.2019.1647158.

Kelly, G. J. (2008). Inquiry, activity and epistemic practice. In R. A. Duschl & R. E. Grandy (Eds.), *Teaching scientific inquiry: Recommendations for research and implementation* (pp. 99–117). Rotterdam: Sense.

Kelly, G. J. (2014). Inquiry teaching and learning: Philosophical considerations. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 1363–1380). Dordrecht: Springer.

Kelly, G. J., & Licona, P. (2018). Epistemic practices and science education. In M. R. Matthews (Ed.), *History, philosophy and science teaching* (pp. 139–165). Dordrecht: Springer.

Kim, M., & Song, J. (2006). The features of peer argumentation in middle school students' scientific inquiry. *Research in Science Education, 36*(3), 211–233.

Kim, M., & Tan, A.-L. (2011). Rethinking difficulties of teaching inquiry-based practical work: Stories from elementary pre-service teachers. *International Journal of Science Education, 33*(4), 465–486.

Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist, 41*(2), 75–86.

Knorr-Cetina, K. D. (1981). *The manufacture of knowledge: An essay on the constructivist and contextual nature of science*. Oxford: Pergamon.

Kreimer, P. (2005). Karin Knorr Cetina. La fabricación del conocimiento. Un ensayo sobre el carácter constructivista y contextual de la ciencia [review of the Spanish version of the book *"The machine of knowledge: an essay on the constructivist and contextual nature of science"*, by K. Knorr-Cetina]. *Redes, 11*(22), 209–216.

Larkin, D. B. (2019). Attending to the public understanding of science education: A response to Furtak and Penuel. *Science Education, 103*(5), 1294–1300.

Lederman, N. G. (2007). Nature of science: Past, present, and future. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (pp. 831–880). Mahwah: Lawrence Erlbaum Associates.

Lederman, N. G. (2019). Contextualizing the relationship between nature of scientific knowledge and scientific inquiry. *Science & Education, 28*(3–5), 249–267.

Lederman, N. G., & Lederman, J. S. (2014). Is nature of science going, going, going, gone? *Journal of Science Teacher Education, 25*(3), 235–238.

Lin, H. S., Gilbert, J. K., & Lien, C. J. (Eds.). (2016). *Science education research and practice in East Asia: Trends and perspectives*. Taipei: Higher Education Publishing.

Mäkitalo-Siegl, K., Kohnle, C., & Fischer, F. (2011). Computer-supported collaborative inquiry learning and classroom scripts: Effects on help-seeking processes and learning outcomes. *Learning and Instruction, 21*(2), 257–266.

Malkawi, A. R., & Rababah, E. Q. (2018). Jordanian twelfth-grade science teachers' self-reported usage of science and engineering practices in the next generation science standards. *International Journal of Science Education, 40*(9), 961–976.

Martins, A. F. P. (2015). Natureza da ciência no ensino de ciências: uma proposta baseada em "temas" e "questões" [Nature of science in science education: a proposal based on "themes" and "questions"]. *Caderno Brasileiro de Ensino de Física, 32*(3), 703–737.

Matthews, M. R. (2012). Changing the focus: From nature of science (NOS) to features of science (FOS). In E. M. S. Khine (Ed.), *Advances in nature of science research* (pp. 3–26). Dordrecht: Springer.

Michaels, S., Shouse, A. W., & Schweingruber, H. A. (2008). *Ready, set, science! Putting research to work in K-8 science classrooms*. Washington: National Academies Press.

Ministry of Education (2008). The Ontario curriculum, grades 1–8. Science and Technology. Retrieved from: http://www.edu.gov.on.ca/eng/curriculum/elementary/scientec18currb.pdf. Accessed 30 Jan 2020.

Minner, D. D., Levy, A. J., & Century, J. (2010). Inquiry-based science instruction —What is it and does it matter? Results from a research synthesis years 1984 to 2002. *Journal of Research in Science Teaching, 47*(4), 474–496.

Mody, C. M. D. (2015). Scientific practice and science education. *Science Education, 99*(6), 1026–1032.

Mulholland, P., Collins, T., Gaved, M., Wright, M., Sharples, M., Greenhalgh, C., ... & Littleton, K. (2009). Activity guide: An approach to scripting inquiry learning. In: *AIED Workshop on Exploratory Learning Environments*, 6-10 Jul 2009, Brighton, UK.

Mullis, I. V. S., Martin, M. O., Goh, S., & Cotter, K. (Eds.) (2016). TIMSS 2015 encyclopedia: Education policy and curriculum in mathematics and science. Retrieved from Boston College, TIMSS & PIRLS International Study Center website: http://timssandpirls.bc.edu/timss2015/encyclopedia/. Accessed 30 Jan 2020.

National Research Council [NRC]. (1996). *National science education standards*. Washington: The National Academies Press.

National Research Council [NRC]. (2000). *Inquiry and the national science education standards*. Washington: The National Academies Press.

National Research Council [NRC]. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington: The National Academies Press.

Newman, W. J., Abell, S. K., Hubbard, P. D., McDonald, J., Otaala, J., & Martini, M. (2004). Dilemmas of teaching inquiry in elementary science methods. *Journal of Science Teacher Education, 15*(4), 257–279.

NGSS Lead States. (2013). *Next generation science standards: For states, by states*. Washington: The National Academies Press.

Nuffield Foundation (2013). *Introduction to model-based inquiry*. Retrieved from: https://www.nuffieldfoundation.org/practical-work-learning/introduction-model-based-inquiry. Accessed 14 Aug 2019.

Öberg, G., & Campbell, A. (2019). Navigating the divide between scientific practice and science studies to support undergraduate teaching of epistemic knowledge. *International Journal of Science Education, 41*(2), 230–247.

Organization for Economic Co-operation and Development [OECD]. (2007). *PISA 2006 science competencies for tomorrow's world. Volume 1: Analysis*. Paris: OECD Publishing.

Organization for Economic Co-operation and Development [OECD]. (2017). *PISA 2015 Science Framework. In PISA 2015 assessment and analytical framework: Science, reading, mathematic, financial literacy and collaborative problem solving*. Paris: OECD Publishing.

Organization for Economic Co-operation and Development [OECD]. (2019). *PISA 2018 assessment and analytical framework*. Paris: OECD Publishing.

Osborne, J. (2014). Teaching scientific practices: Meeting the challenge of change. *Journal of Science Teacher Education, 25*(2), 177–196.

Prins, G. T., Bulte, A. M., & Pilot, A. (2018). Designing context-based teaching materials by transforming authentic scientific modelling practices in chemistry. *International Journal of Science Education, 40*(10), 1108–1135.

Ramnarain, U. (2018). Scientific literacy in East Asia: Shifting toward an inquiry-informed learning perspective. In *Primary science education in East Asia* (pp. 201–213). Cham: Springer.

Reiser, B. J., Tabak, I., Sandoval, W. A., Smith, B. K., Steinmuller, F., & Leone, A. J. (2001). BGuILE: Strategic and conceptual scaffolds for scientific inquiry in biology classrooms. In *Cognition and instruction: Twenty-five years of progress* (pp. 263–305). Mahwah: Erlbaum.

Rocard, M., Csermely, P., Jorde, D., Lenzen, D., Walberg, H., & Hemmo, V. (2007). *Science education now: A renewed pedagogy for the future of Europe*. Brussels: Directorate General for Research, Science, Economy and Society.

Rönnebeck, S., Bernholt, S., & Ropohl, M. (2016). Searching for a common ground–A literature review of empirical research on scientific inquiry activities. *Studies in Science Education, 52*(2), 161–197.

Rundgren, C. J. (2018). Implementation of inquiry-based science education in different countries: Some reflections. *Cultural Studies of Science Education, 13*(2), 607–615.

Sampson, V., & Gleim, L. (2009). Argument-driven inquiry to promote the understanding of important concepts & practices in biology. *The American Biology Teacher, 71*(8), 465–472.

Sampson, V., Grooms, J., & Walker, J. (2009). Argument-driven inquiry: A way to promote learning during laboratory activities. *The Science Teacher, 76*(7), 42–47.

Sandoval, W. A. (2005). Understanding students' practical epistemologies and their influence on learning through inquiry. *Science Education, 89*(4), 634–656.

Stroupe, D. (2014). Examining classroom science practice communities: How teachers and students negotiate epistemic agency and learn science-as-practice. *Science Education, 98*(3), 487–516.

Stroupe, D. (2015). Describing "science practice" in learning settings. *Science Education, 99*(6), 1033–1040.

Swain, F. (2019). Is it right to use Nazi research if it can save lives? *BBC.com*. Retrieved from http://www.bbc.com/future/story/20190723-the-ethics-of-using-nazi-science. Accessd 24 July 2019.

Tang, X., Coffey, J. E., Elby, A., & Levin, D. M. (2010). The scientific method and scientific inquiry: Tensions in teaching and learning. *Science Education, 94*(1), 29–47.

Volkmann, M. J., & Abell, S. K. (2003). Seamless assessment. *Science and Children, 40*(8), 41–45.

Vorholzer, A., & von Aufschnaiter, C. (2019). Guidance in inquiry-based instruction–An attempt to disentangle a manifold construct. *International Journal of Science Education, 41*(11), 1562–1577.

White, B. Y., & Frederiksen, J. R. (1998). Inquiry, modeling, and metacognition: Making science accessible to all students. *Cognition and Instruction, 16*(1), 3–118.

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education, 92*(5), 941–967.

Yoon, H. G., Joung, Y. J., & Kim, M. (2012). The challenges of science inquiry teaching for pre-service teachers in elementary classrooms: Difficulties on and under the scene. *Research in Science Education, 42*(3), 589–608.

Yoon, S. Y., Suh, J. K., & Park, S. (2014). Korean students' perceptions of scientific practices and understanding of nature of science. *International Journal of Science Education, 36*(16), 2666–2693.

Zangori, L., & Forbes, C. T. (2014). Scientific practices in elementary classrooms: Third-grade students' scientific explanations for seed structure and function. *Science Education, 98*(4), 614–639.

Zhang, L. (2016). Is inquiry-based science teaching worth the effort? Some thoughts worth considering. *Science & Education, 25*(7–8), 897–915.