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Integrating the epistemic and ontological aspects of content knowledge in science teaching and learning

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ABSTRACT

Promoting facility with content knowledge is one of the most important objectives of science teaching. Conventionally, the focus for this objective is placed on the substantive side of content knowledge (e.g. science concepts/laws), whereas its epistemic or ontological aspects (e.g. why do we construct concepts?) rarely receive explicit attention. In this article, we develop a theoretical argument for the value of elevating the attention paid to the epistemic/ontological aspects of content knowledge and integrating them with its substantive side. Our argument is structured in two parts. The first unpacks the epistemic/ontological aspects of content knowledge and their role in science. For this, we focus on two specific aspects (i.e. ontological status and epistemic value of science concepts), which we elaborate in the context of two particular content domains, namely magnetism and energy. The second part of the argument highlights the potential of discourse on epistemic/ontological aspects to facilitate learning in science. We delineate how such discourse could (a) promote coherent conceptual understanding, (b) foster a productive epistemological stance towards science learning, and (c) enhance students' appreciation of ideas associated with the nature of science. The article concludes with a discussion of ensuing implications for science education.

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Introduction

Standards documents (e.g. AAAS, 1993; NRC, 2007, 2012, 2013) have emphasised the integration of disciplinary knowledge with the scientific practices. However, the epistemological aspects of either scientific practices or disciplinary knowledge have remained largely implicit. This is in contrast with the widely acknowledged position that the development of informed views on the epistemic underpinnings of science constitutes an important aspect of being proficient in science (Duschl, Schweingruber, & Shouse, 2007). They also deviate from promoting coherence in student understanding and downplay the value of theoretical abstraction for developing the transferable knowledge necessary for scientific expertise and creative problem solving.

Explicit focus on epistemology could serve a productive role in science learning from the early years. By epistemology we refer to the fundamental ideas associated with how

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knowledge in science is developed, justified, and elaborated. Helping students develop an appreciation of such ideas has been long and widely recognised as a central component of science learning (Central Association for Science and Mathematics Teachers, 1907; Duschl, 1990; Duschl et al., 2007; Millar & Osborne, 1998; NRC, 1996; Robinson, 1965). The existing research literature has explicitly addressed the value of integrating epistemic considerations with scientific practices (Berland et al., 2016; Ford, 2008b). Appreciating the epistemic underpinnings of a scientific practice is thought to enhance students' ability to enact it in a purposeful manner that coheres with authentic science. In this article, we seek to extend this argument to the science disciplinary content knowledge and contribute to the development of a more holistic theoretical view for the educational elaboration of the epistemic and ontological aspects of scientific knowledge.

Helping students to understand and use disciplinary content knowledge is one of the most emphasised objectives of science education standards (AAAS, 1993; Millar & Osborne, 1998; NRC, 2007, 2012, 2013). The conceptualisation of this learning objective tends to focus solely on the substantive side of content knowledge, i.e. the content attached to the various concepts per se. Optimally, this substantive side involves acquaintance with operational definitions of relevant concepts or the ability to apply the concepts as constituents of conceptual models for the analysis of physical systems (McDermott et al., 1996). One component commonly missing from this conceptualisation of facility with disciplinary content knowledge is its epistemic underpinnings and ontological considerations. Indicatively, in the case of the concept of force, whereas the substantive side would involve the ability to identify the forces exerted between the objects in a given system and apply Newton's laws, this latter component involves building understanding about the nature of force as a construct (a *conceived physical quantity*, as opposed to a material substance) and its purpose in science (to describe qualitatively and quantitatively a certain *process* that manifests itself in particular ways, e.g. as a push or pull between objects *causing* changes in the state of motion). The emphasis in conventional science teaching practice is often placed on the substantive side, whereas the epistemic and ontological considerations receive only scant attention in a fragmentary manner. In this article, we take the perspective that supplementing the substantive side with epistemic/ontological considerations could serve a productive role in enhancing the coherence of the ensuing conceptual understanding.

Purpose and structure of the article

We seek to develop a theoretical argument for explicit attention to the epistemic underpinnings and ontological considerations of content knowledge in the science classroom. The integration between the elaborated content knowledge and its epistemic/ontological aspects has received some attention within the research literature about the nature of science (NOS) (Abd-El-Khalick, 2012; Lederman, 2007). However, this has emanated from a very different perspective. The focus has been on the question of whether NOS ideas can be better addressed when contextualised in the conceptual framework of science (Bell, Matkins, & Gansnede, 2011; Khishfe, 2008; Khishfe & Lederman, 2006). We seek to complement this research line by delineating the actual integration between content knowledge and its epistemic/ontological aspects. This issue remains largely under-theorised.

Our main question in this article is: what could be the content of facility with the epistemic and ontological aspects of content knowledge and why is this learning objective important for science education?

The article is structured in three main sections. The first sets out to unpack the notion of the epistemic and ontological aspects of science content knowledge. The second elaborates on how addressing these aspects in the classroom discourse could enhance science learning. The third section discusses ensuing implications for research in science education, including on the contextualisation of NOS ideas within science content knowledge.

Ontological and epistemic aspects of science content knowledge for school science: delineating their scope

In an attempt to operationalise the meaning we attach to the epistemic and ontological aspects of science content knowledge, we focus on two specific ideas, namely the *ontological status* and the *epistemic value* of science concepts. The *ontological status* of a concept refers to its very nature as a construct and differentiates it from other ontologies such as objects, phenomena, scientific laws, or models. On the other hand, *epistemic value* refers to the added value that a concept brings to the overall purpose of science to build interpretive and predictive power (Brigandt, 2010; Holton & Brush, 2001; Theobald, 1966). This section sets out to delineate these two constructs.

The notions of ontological status and epistemic value have been a topic of discussion within the philosophy of science (Brigandt, 2010; Ladyman, 2002). Ontology has also received considerable attention within science education research but this has been primarily focused on its facility to account for the source of students' conceptual difficulties (Chi, Slotta, & Leeuw, 1994; Slotta, Chi, & Joram, 1995). The role of these two notions in science teaching and their potential impact on science learning remain understudied.

Targeting a reasonable level of complexity: a note of caution

The philosophical discourse underlying the notions of ontological status and epistemic value tends to be highly abstract and complex. For instance, ontology has been surrounded with extensive discourse on a range of topics, including the ontological status of theoretical, sub-atomic entities (Maxwell, 1962) and the various perspectives (e.g. realism and instrumentalism) on whether scientific theories and their entities exist in nature (Ladyman, 2002). This discourse is very much removed from school science. The position taken in this article reflects the consensus view established within the science education community (Lederman, 2007; McComas, 2000; Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003): science teaching cannot (and should not) aim at deep philosophical discourse. Rather, it should pursue a simplified and even vulgarised account, integrating fundamental epistemic ideas. These ideas should be (a) simple enough to lend themselves to teaching elaboration in school science, (b) sufficiently uncontroversial, so that disagreements among philosophers of science can remain reasonably unexplored, and (c) likely to serve a productive role in the students' learning trajectories. We propose that ontological status and epistemic value could be dealt with in school science in a simplified form satisfying these three criteria.

The next section illustrates the notions of ontological status and epistemic value in the context of two examples drawn from content domains that are common in school science, namely magnetism and energy. The selection to focus on these two domains is not intended to imply that they relate to the notion of ontological status or epistemic value in a different way than any other science domain. Indeed, it would have been possible to draw on many other examples. However, we believe that the selected domains allow us to convey a broad sense of the notions of epistemic value and ontological status.

Illustrating the notions of epistemic value and ontological status in context

This section is intended to illustrate the notions of ontological status and epistemic value in the context of magnetism and energy. The two domains are considered in separate sections. Each section begins with a discussion of how the substantive side of the respective content knowledge could be drawn upon for the analysis of relevant phenomena. The emphasis is then shifted to the notions of ontological status and epistemic value with a view to illustrate how they could be brought to bear on these same domains.

Example I: Magnetism

Some phenomena commonly addressed in secondary school science are (a) the magnetisation of ferromagnetic materials, (b) the interaction between magnets brought close to each other in different spatial configurations, and (c) the interaction between a magnet and a compass. In deriving qualitative interpretations for such phenomena, students are expected to develop coherent, self-consistent accounts drawing on relevant concepts. At the collective level, these concepts constitute the *content space* of the domain of interest. The content space can vary substantially in terms of depth and breadth in accordance with the level of detail and sophistication appropriate for the target student population. In secondary school, the content space for the phenomena mentioned above could include varying emphases on the magnet, the idea of repulsion/attraction, and the notions of magnetic force, magnetic domains, magnetic field, and magnetic field lines.

Facility with the substantive side of content knowledge. Facility with the substantive side of disciplinary content knowledge essentially involves the ability to employ the relevant concepts and models in order to build coherent interpretive accounts for specific phenomena. For instance, the model of magnetic domains could be drawn upon to account for the changes occurring in the magnetisation of ferromagnetic materials. In a similar manner, the ideas of magnetic field and magnetic field lines could be employed to account for interaction at a distance, including the alignment of a compass placed nearby a magnet.

Appreciation of epistemic/ontological aspects of content knowledge

Appreciation of ontological status. An important idea in magnetism is the distinction, in ontological status, between key elements of the corresponding content space. Students can be usefully guided to appreciate that a magnet is a *discovered* physical object identifiable with specific features (i.e. it attracts ferromagnetic materials, it attracts or repels other magnets, and it neither attracts nor repels objects made from a wide range of other materials, including most metals). Repulsion and attraction, on the other hand, refer to observable instances of interaction between magnets or between magnets and ferromagnetic materials. Magnetic force, magnetic field, and field lines are *human-conceived* constructs representing either physical quantities (force and field) or representation devices (field lines). Unlike a magnet, which is an actual physical object, these constructs do not have a counterpart in the material physical world (Cassidy, Holton, & Rutherford, 2002).[1]

Appreciation of epistemic value. Epistemic value is intended to capture the added value a physical concept brings to our ability to account for and predict the temporal evolution of physical systems or phenomena. In the case of magnetism, students can appreciate that magnetic force is intended to offer a measure of the strength of the interaction between magnetic objects. For instance, it can be used to account for the magnitude of the acceleration of a paper clip towards a magnet. In a similar manner, the notion of the magnetic field provides a powerful scheme for analysing interactions between objects at a distance.[2] Finally, the epistemic value of field lines relates to mapping the direction of a magnetic field and representing how its magnitude varies at different locations.

Example II: Energy

Energy is widely recognised as a major learning objective of school science, starting from primary school (Lacy, Tobin, Wiser, & Crissman, 2014; NRC, 2012; Papadouris & Constantinou, 2011). It entails certain features (i.e. energy transfer, form conversion, conservation, and degradation), which could be used in a concerted manner to offer interpretive accounts for a wide range of phenomena drawn from diverse domains (Duit, 2014). These features, in conjunction with the various forms of energy, could be conceived of as comprising the content space associated with the domain of energy at secondary school level.

Facility with the substantive side of disciplinary content knowledge. Facility with this side of disciplinary content knowledge of energy involves drawing on the features of energy to develop coherent interpretations for the operation of physical systems (Papadouris & Constantinou, 2016; Duit, 2014) and making appropriate use of the language of forms of energy (Duit, 2014; Kaper & Goedhart, 2002). For instance, the features of form conversion and energy transfer could be drawn upon to offer interpretive accounts for changes occurring in physical systems (Papadouris, Constantinou, & Kyratsi, 2008). For example, consider a compressed spring positioned horizontally with one end fixed on a stationary surface and a ball placed at its other end. Upon decompression, the spring pushes the ball causing it to accelerate from rest along a level horizontal surface. This change (acceleration from rest) could be accounted for qualitatively by means of energy transfer (from the spring to the ball) and form conversion (from elastic potential energy in the compressed spring to kinetic energy of the ball). Another example pertains to a set of two magnets held at a certain distance, which start accelerating towards each other upon release. This change (acceleration of the two magnets from rest) is associated with energy transfer (from the system of the two magnets – or put more formally from the magnetic field generated by the two magnets – to each of the individual magnets) and form conversion (from magnetic potential energy in the magnetic field to kinetic energy in the two magnets).

Energy conservation and degradation could be drawn upon to supplement these interpretive accounts. Specifically, in the previous examples, the maximum value of the kinetic energy of the ball (or the sum of the amounts of kinetic energy of the two magnets) cannot exceed a limiting value corresponding to the amount of elastic potential energy initially stored in the spring (or the total amount of magnetic potential energy stored in the system of the two magnets). Finally, the feature of energy degradation could be drawn upon to account for how the total amount of kinetic energy in each of the two cases will be lower than this limiting value; energy tends to degrade in quality through dissipative processes that essentially transfer energy to the surrounding environment through the process of heat (Duit, 2014; Millar, 2014).

Appreciation of epistemic/ontological aspects of content knowledge

Appreciation of ontological status. The ontological status of energy is captured by the fundamental question 'what is the nature of energy?'. Students could be usefully guided to appreciate energy as a human-conceived construct. Energy is a theoretical construct rather than a concrete physical object or other material residing in the natural world. At a more advanced level, students could be usefully guided to construe energy as a mathematical quantity (Feynman, Leighton, & Sands, 1965), a property that describes one aspect of the state of a system.

Addressing the ontological status of energy is entangled with the various technical terms referring to the different forms of energy (Kaper & Goedhart, 2002; Millar, 2014). Depending on the phenomenology of the system under analysis, it is common to invoke different terms referring to forms of energy. Pursuing an appropriate understanding of the ontological status of energy should aim at helping students appreciate that these terms represent different ways in which a single entity (i.e. energy) could be stored in a system, rather than entities of a different nature (Papadouris & Constantinou, 2014b; Millar, 2014). At a more advanced level, students can understand that energy storage in a system is a metaphor for the value of energy as a property of that system.

Appreciation of epistemic value. Perhaps the most important aspect of the epistemic value of energy is its unifying, cross-cutting nature (Arons, 1999; Holton & Brush, 2001; NRC, 2012). Unlike many other concepts in science, energy is not specifically linked to a particular domain of phenomena. Rather, it transcends individual domains by offering a unified approach to analysing physical phenomena (Arons, 1999; Holton & Brush, 2001). Helping students appreciate the unified perspective afforded by energy and its importance to science could enhance their ability to use energy as a framework for interpreting physical phenomena (Constantinou & Papadouris, 2012, Papadouris & Constantinou, 2014b, 2016; Lacy et al., 2014).

In addition to the epistemic value of energy, it is also important to guide students in understanding the epistemic value of the individual features of energy (transfer, transformation, conservation, and degradation): i.e. how each of these features contributes to the interpretive or predictive power of energy as a framework for analysing the operation of physical systems (Papadouris et al., 2016; Lacy et al., 2014). Specifically, energy transfer and transformation can be used to provide interpretive accounts for changes observed in physical systems. Energy conservation and energy degradation enable us to make predictions about the temporal evolution of physical systems: energy conservation allows predicting what cannot occur in a physical system. It restricts the possible configurations of a system by excluding those not conserving energy (Duit, 2014; Feynman et al., 1965). Energy degradation enables predictions of what is highly likely to occur in a system because of the tendency of energy to degrade in quality through dissipative processes (e.g. heat).

Appreciating the unique contribution conferred by each of these features could promote more informed and meaningful engagement of students with the employment of energy as a framework for analysing physical systems (Papadouris & Constantinou, 2014a). Also, it could facilitate the development of generalisable understanding of how theoretical/conceived constructs are used in science to facilitate interpretation and prediction (Holton & Brush, 2001).

A note on the domain-specific character of the epistemic/ontological aspects of content knowledge

The epistemic and ontological aspects of content knowledge are specifically anchored to individual domains (e.g. magnetism or energy). However, it is important to note that it is possible to identify similarities seeming to be relevant to the science disciplinary knowledge more broadly. One such example relates to the idea that the body of science knowledge includes both empirical content and theoretical content. For instance, the first could involve the observational data, whereas the latter could involve the human-conceived constructs intended to facilitate sense-making and interpretation of the observational data. Making this distinction between these two parts of the body of science knowledge constitutes a key idea generalising to essentially any topic within science. In addition, there are also less generic similarities confined within a narrower set of domains. For instance, the discussion of the ontological status and epistemic value of magnetism could be extended to phenomena involving electrostatic or gravitational forces. The notions of force, field and field lines also appear in these domains and retain the same ontological status and epistemic value as in the discussion on magnetism.

While there might be similarities across different domains, there might also be substantial differences that need to be carefully dealt with. For instance, even though the epistemic goal associated with the unified representation of phenomena applies to both the concepts of field and energy, there is a substantial difference in terms of pervasiveness: the notion of field provides a powerful framework restricted to a certain range of domains, such as physical systems involving electromagnetic or gravitational interactions. On the other hand, energy provides a far more pervasive framework for the analysis of physical systems drawn from essentially any domain of Natural Science including Thermodynamics, Mechanics and Electrodynamics, as well as biological and chemical systems. An emerging appreciation of possible connections and differences in the epistemic/ontological aspects of different domains could substantially enhance students' facility with content knowledge about these domains but also their understanding of the structure of science disciplinary knowledge.

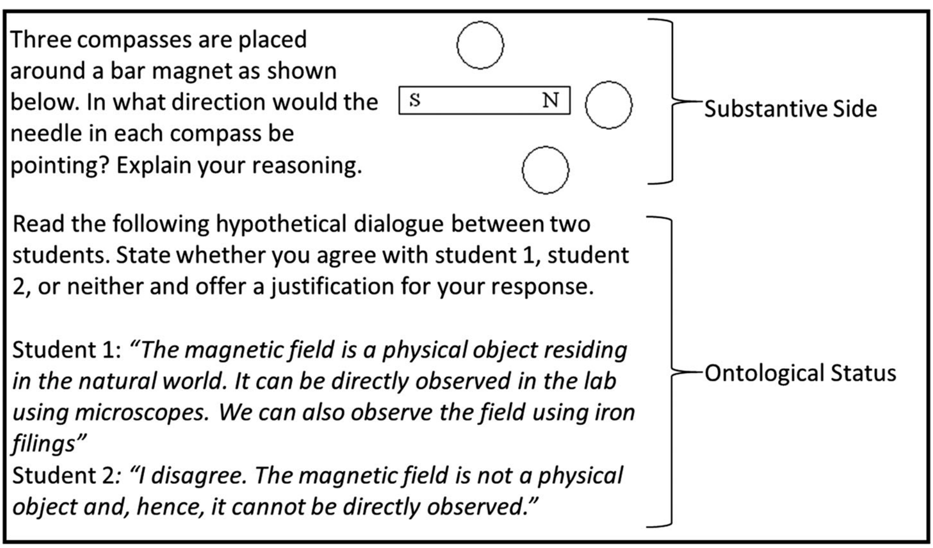
A note on the interaction between the substantive side of content knowledge and the epistemic/ontological considerations in the classroom

We envisage the substantive side of content knowledge and its associated epistemic/ontological aspects as two components of the classroom discourse that can unfold in unison, in an integrated manner. To illustrate this, the attempt to help students develop energy as a tool for analysing the operation of physical systems could be supplemented with the elaboration of its ontological status as a non-material physical quantity and its epistemic value for the unification of the analysis of disparate physical systems (e.g. from thermodynamics and mechanics). In a similar manner, while seeking to elaborate the notion of the magnetic field and encourage students to employ it for the analysis of relevant physical systems, it would be useful to initiate a thread of discourse on the ontological and epistemic aspects of this concept.

Figures 1 and 2 provide an illustration of how the substantive side of content knowledge and its associated epistemic/ontological aspects could be integrated in the classroom discourse. These figures describe an indicative teaching/learning activity for magnetism and energy, respectively.

Potential contribution of explicit discourse about epistemic/ontological considerations to science learning

Helping students develop informed conceptions of fundamental ideas associated with the epistemic/ontological aspects of core concepts in science constitutes a significant learning objective in its own right. In addition, we believe that pursuing this objective is likely to contribute to science learning more broadly. In particular, it could serve the purpose of (a) promoting coherent, holistic conceptual understanding of science content knowledge, (b) helping students develop an informed epistemological stance towards science teaching/learning, and (c) enhancing students' appreciation of fundamental ideas associated with NOS. This section elaborates on these three aspects.



This activity represents a revised form of a task included in the Physics by Inquiry curriculum materials (McDermott et al., 1996).

Figure 1. Illustrative teaching/learning activity in the context of magnetism.

A ball is placed in front of a compressed spring which is allowed to uncoil. The ball then starts accelerating from rest along a level surface. After covering a short distance, the ball eventually comes to rest.

a. Where was the energy at the beginning (when the ball was initially at rest) and at the end (when the ball eventually came to rest again)? How is this consistent with the energy conservation principle?
b. Use the features of energy transfer and form conversion to describe the initial acceleration of the ball from rest.

Substantive Side

c. It would have been possible to build a description for the acceleration of the ball without employing energy, at all. Why is energy needed in science?

Epistemic Value

Figure 2. Illustrative teaching/learning activity in the context energy.

Promoting coherent conceptual understanding of science content knowledge

Productive engagement with the conceptual analysis of physical phenomena is predicated on the ability to competently deal with content knowledge. In broad terms, this includes selecting appropriate concepts and principles and applying them in an effective manner to analyse the phenomenon under consideration (Ding, Chabay, & Sherwood, 2013; McDermott, 2001). Placing emphasis on the epistemic and ontological aspects of content knowledge could serve a productive role in facilitating more coherent, holistic conceptual understanding. We envision two different mechanisms promoting this goal: (a) pre-empting/addressing conceptual difficulties and (b) guiding/constraining the employment of content knowledge. Next, we elaborate on each of these two mechanisms.

Pre-empting and addressing conceptual difficulties

Students' ability (or lack thereof) to attach an appropriate ontological status to a concept could have an important impact on their understanding of that concept. A well-documented finding illustrating this relates to students' tendency towards substance-based reasoning (Reiner, Slotta, Chi, & Resnick, 2000). Below we consider three examples that demonstrate how this tendency could beguile students into the erroneous conceptualisation of physical quantities as substance-like entities.

The first example relates to the students' tendency to conceive of field lines as real entities residing in the material natural world (Guisasola, Almudí, & Zubimendi, 2004). There is evidence suggesting that even science undergraduates, who have extensive experiences with the analysis of physical systems drawing on the ideas of field and field lines, tend to commit to this materialistic perspective (Pocovi & Finley, 2002; Törnkvist, Pettersson, & Tranströmer, 1993). Appealing to this erroneous ontological status of field or field lines might not compromise, in a profound manner, students' ability to tackle the standard quantitative exercises that usually lie at the heart of conventional teaching. However, it does question the extent to which it would be reasonable to ascribe these students with coherent understanding of these concepts. Broadening the aims of teaching to explicitly address the epistemic/ontological aspects of field or field lines could help students recognise and address the distorted ontologies they are attributing to these concepts and, hence, serve as a stepping stone towards stronger, holistic conceptual understanding.

Another example relates to the well-documented tendency of students to identify electric current with a material-like entity. This tendency could yield non-valid accounts for relevant phenomena. One indicative example is the notion of storing or consuming electric current (Reiner et al., 2000). Another example pertains to the tendency to attribute the glow of a bulb in an electric circuit to the increased concentration of electric current along the filament inside the bulb (Papadouris et al., 2008). Promoting discourse in the classroom about epistemic/ontological aspects could help to lift the flaw inherent in the characterisation of electric current as a substance. For instance, it could help students appreciate electric current as a model of a process taking place in a complete circuit, rather than a material substance (Reiner et al., 2000).

Finally, another example illustrating this same argument relates to the students' tendency to conceive of force as an intrinsic property of objects (Driver, Squires, Rushworth, & Wood-Robinson, 1994). Helping students appreciate that, ontologically, force constitutes a physical quantity that quantifies an *interaction* between two objects (push or pull), rather than an intrinsic property of individual objects, places students in a much better position to develop an acceptable notion of the concept of force (Dekkers & Thijs, 1998). For instance, it could facilitate appreciation of the idea that weight is not a property of isolated objects; rather, it is the gravitational force emerging due to the interaction between everyday objects and the earth (or, put more formally, between the mass of interest and a gravitational field).

Guiding and constraining the employment of content knowledge

The available research literature has extensively documented students' tendency to draw on science concepts in a superficial manner, which is often at variance with their intended use in science (Docktor & Mestre, 2014; Finkelstein, 2005; van Heuvelen, 1991; Mazur, 1997; McDermott, 2001; Redish, 2014). An example illustrating this, borrowed from Hutchison and Hammer (2010), relates to a classroom episode where students are reasoning with the ideal gas law to estimate the difference in the air pressure between the floor and the ceiling of a given room. The students employ the mathematical expression '$PV = nRT$' but tend to subscribe to the erroneous hypothesis that 'R' refers to the radius of some disc, rather than the gas constant. While these students appear to use a seemingly legitimate conceptual tool (i.e. the ideal gas law) they do so in a manner deviating from the physical meaning of its various terms and, hence, its intended use in science.

Systematically complementing the classroom discourse on content knowledge with a component that focuses on epistemic/ontological considerations could foster a more thoughtful stance, on the part of the students, placing them in a position where they keep themselves accountable as to the content and physical meaning of the various terms they are invoking. A variant of this argument has appeared in the literature on helping students develop facility with the practices of science, such as the design and conduct of empirical investigations and the analysis and interpretation of data (NRC, 2012). It has been argued that students who understand the purpose and importance of the scientific practices would be better positioned to determine when and how to enact those practices compared to students who are merely able to apply certain parts of the practices (e.g. variable control strategy) in an algorithmic manner (Ford, 2008a, 2008b). We would like to extend this argument to disciplinary content knowledge. Our argument is that fostering student commitment to systematic reflection on the epistemic/ontological aspects of content knowledge could serve as a mechanism for managing and constraining how they use concepts/conceptual tools. This, in turn, could increase the likelihood for using concepts in a manner resonating with their intended role and their physical significance in the realm of science.

Fostering a productive epistemological stance towards the science learning environment

Engaging students in explicit discourse about the epistemic/ontological aspects of content knowledge is likely to facilitate an appropriate framing of the teaching/learning situations unfolding in the science classroom. Framing essentially refers to how one contextualises and perceives the specific situation in which he or she finds himself or herself. This, in turn, shapes the lens to be employed for making sense of what is involved in that situation (Goffman, 1974). For instance, framing influences one's decisions (implicit or explicit) as to (a) how to interact with the information involved in a certain situation (e.g. determine what information to attend to or suppress) and (b) the knowledge they will deem relevant and, hence, select to draw upon (Redish, 2014). The notion of framing has been widely recognised as an essential element of any attempt to interpret the perspective taken by students when interacting with the various teaching/learning situations they encounter in the science classroom (Engle, 2006; Finkelstein, 2005; Hammer, Elby, Scherr, & Redish, 2005; Hutchison & Hammer, 2010; Redish, 2014; Scherr & Hammer, 2009).

Some typical examples of teaching/learning situations that appear in the science classroom are the introduction and elaboration of concepts, principles, or laws and their application for the analysis of specific systems or phenomena. Conventionally, the teaching approach taken in such situations favours the presentation of canonical domain knowledge (e.g. definitions, laws, and principles) in a finished and static form (Duschl, 1990; Kesidou & Roseman, 2002). This approach is in stark contrast to the wide recognition of the need to engage students in classroom activities reflecting essential aspects and processes of authentic science (Engle & Conant, 2002; Ford & Forman, 2006; O'Neill & Polman, 2004). Emphasising epistemic/ontological aspects of content knowledge could contribute towards facilitating an appropriate framing of the classroom discourse. For instance, it could help students appreciate the idea that science includes a (limited) range of constructs of different ontology. Initially, this could be restricted to a coarse level of detail focusing, for instance, on the broad distinction between physical objects, observational data, and theoretical constructs for the interpretation/prediction of physical phenomena. The level of detail and abstraction could be significantly elevated in subsequent grade levels to include subtler, cognitively more demanding aspects (e.g. the distinction between the magnetic force and magnetic field as mathematical constructs of a different kind, i.e. vector and vector field, respectively).

Students tend to subscribe to the epistemologically misleading conceptualisation of content knowledge as a loose collection of disparate formulae and technical terms (Docktor & Mestre, 2016; Hammer, 1994; Redish, Saul, & Steinberg, 1998). Helping students develop appreciation of the structure and coherence underlying content knowledge could facilitate the shift away from this conceptualisation. It could foster a more informed epistemological stance favouring the pursuit of deep understanding rather than the memorisation of definitions, formulae, and algorithms for solving quantitative exercises (Docktor & Mestre, 2014; Elby, 2001; Mazur, 1997; Redish, 2014). In addition, it is likely to enhance and sustain students' interest and positive attitudes towards science (Lin, Deng, Chai, & Tsai, 2013; Tsai, 1998). These affective variables hold a significant role in creating conditions that are conducive to learning (Hidi & Renninger, 2006).

Enhancing students' appreciation of ideas associated with NOS

NOS has been introduced in the science education research literature as a construct encapsulating key ideas associated with the philosophical underpinnings of science, its practices and its products, which could be usefully elaborated in school science (Abd-El-Khalick, 2012; Lederman, 2007; McComas, 2000). Any attempt to engage students with discourse about the ontological status and epistemic value of science concepts (e.g. magnetic field or energy) is entangled with NOS. This could be illustrated in the context of one of the most widely acknowledged aspects of NOS, namely the idea that while science is an evidence-based enterprise it also draws largely on human creativity (Lederman, 2004, 2007; McComas, 2000; Osborne et al., 2003). This aspect has been recognised as a useful learning objective for school science starting from an early stage (Akerson, Nargund-Joshi, Weiland, Pongsanon, & Avsar, 2014). One important idea under this aspect relates to the distinction between observation and interpretation (or inference) (Lederman, 2007; McComas, 1998; Osborne et al., 2003). Observations refer to information about the operation of a phenomenon of interest. This information is accessible to our senses, or to their extension (e.g. the microscope or the telescope). On the other hand, interpretation emerges as a human-constructed inference purporting to account for how the phenomenon of interest unfolds the way it does (Braaten & Windschitl, 2011; Lederman, 2007). Thus, while science is bounded by the available observational data, it also largely draws on human invention and creativity within certain constraints imposed by the set of values and norms shared by the scientific community (Holton & Brush, 2001).

The idea that science contains both an empirical (e.g. the observational data) and a theoretical component (e.g. the concepts invented to account for the observations) resonates well with the meaning we wish to attach to the epistemic and ontological aspects of content knowledge. In particular, this idea underlies the discussion about the variation in the ontological status of the range of entities discussed earlier in the examples of magnetism and energy. For instance, the magnet, as a physical object, and the observable interactions between a magnet and a ferromagnetic object are instances of the empirical component of disciplinary knowledge about magnetism. On the contrary, magnetic field, magnetic field lines, and magnetic force fall under its theoretical component; they are theoretical constructs, conceived to enable self-consistent, coherent, interpretive accounts of observational data involving magnetic interactions. Engaging students with explicit discourse about the epistemic/ontological aspects of content knowledge seems likely to foster informed understandings of NOS.

Connections to science education research and ensuing implications

In this section, we consider the implications that ensue from the theoretical ideas elaborated in this article with respect to science education research. Specifically, we focus on the implications for (a) research on NOS and the development of learning environments to promote this objective, and (b) research on the development of a more robust theorisation of conceptual understanding (i.e. facility with content knowledge).

Implications for NOS research

The extensive attention received by NOS has substantially enhanced the understanding of the science education community about NOS as a learning objective (for elaborate reviews of the extant research, the reader is referred to Deng, Chen, Tsai, & Chai (2011) and Lederman (2007)). Notwithstanding the significant advancements in research on NOS, there is clearly a need for further work. One vitally important area within this field relates to the issue of how to take ideas associated with NOS into the science learning environment and usefully interweave them with other important learning objectives, including the development of content knowledge. Even though this area has received extensive attention yielding important insights (Bell, Mulvey, & Maeng, 2016; Khishfe & Abd-El-Khalick, 2002; Khishfe & Lederman, 2006; Lederman, 2007; Lederman & Abd-El-Khalick, 1998) there is a clear need for further work to better theorise this topic.

The extant literature identifies two distinct approaches to introducing and elaborating NOS in the classroom environment. These approaches vary depending on the context attached to the discourse (contextualised versus non-contextualised). The non-contextualised approach seeks to engage students in reflection on ideas pertinent to NOS in a context that is totally removed from the body of disciplinary content knowledge [see Lederman and Abd-El-Khalick (1998) for specific examples]. On the contrary, the contextualised approach explicitly anchors the epistemic discourse to the conceptual framework of science. This latter approach has been referred to as the integrated approach (Khishfe & Lederman, 2006; Khishfe, 2015; Lederman, 2007). The term 'integrated' was primarily intended to make the distinction between the contextualised and non-contextualised approach more pronounced, with significantly less attention being paid to the substance of how NOS actually gets interweaved and coupled with content knowledge. For instance, within a contextualised approach content knowledge is often restricted to the role of merely providing the framing for the epistemic discourse by seizing the opportunities afforded by the elaboration of content knowledge to elicit discussion about relevant philosophical ideas. To illustrate this point, while engaging with activity sequences that involve developing a model to represent a phenomenon and account for its operation (e.g. greenhouse effect), students could also be engaged with discussion on the often unnoticed (albeit important) idea that while models are of paramount importance in science they cannot be exact replicas of their referent system (Bell et al., 2011; Grosslight, Unger, Jay, & Smith, 1991; Ingham & Gilbert, 1991). One characteristic of this contextualised approach to the teaching of NOS is that the connection between content knowledge and epistemic discourse typically tends to run only in one direction. In particular, content knowledge serves to situate (or trigger) epistemic discourse that, once initiated, unfolds independently along a separate thread, often removed from the specific content knowledge.

The argument elaborated in this article in support of elevating the attention being paid to discourse about epistemic/ontological aspects could provide an alternative perspective into the integration between NOS and content knowledge. This perspective envisages a more dynamic, bi-directional connection between NOS and content knowledge in the sense that the teaching elaboration of science concepts is explicitly coupled with discourse about aspects of the epistemic value and the ontological status of these same concepts. For instance, the elaboration of how the magnetic field and its field lines can be used to account for interactions between magnetic objects could be supplemented with explicit discourse about the epistemic goal they are intended to serve (i.e. enable the analysis of systems involving magnetic interactions) and their ontological status (i.e. physical quantities invented in science as opposed to the magnet, which is a physical object, and the instances of repulsion/attraction, which are observational data). In the case of energy, the teaching/learning activities employed to engage students in the process of analysing the operation of physical phenomena could be usefully coupled with reflective discourse about the invented nature of energy as an interpretive framework unifying the analysis of phenomena regardless of the domain they are drawn from.

The alternative perspective described above could offer a powerful means of infusing NOS ideas in the science classroom in a manner that could afford deeper and stronger integration between NOS and the science content. This could be connected to the distinction made between the approaches that tend to focus on students' conceptions of the nature of professional science, on the one hand, and the approaches that capitalise, instead, on students' own efforts to make scientific meaning of the world (Sandoval, 2014). The perspective elaborated here could offer a possible way of linking these two currently disconnected approaches.

Further research is needed to adequately elaborate and articulate the key aspects of the proposed alternative approach to integrating NOS with content knowledge. Some areas of research that could be usefully explored are the (a) documentation of the aspects of NOS that could be promoted through discourse on the epistemic/ontological aspects of content knowledge, (b) development of teaching innovations embodying this integrated approach, (c) exploration of how students actually receive and respond to such innovations and the corresponding discourse they involve, and (d) investigation of the potential effectiveness of this approach in promoting NOS understanding, in comparison to other approaches.

Need for stronger theorisation of 'conceptual understanding' as a learning objective

The fact that conceptual understanding constitutes one of the most widely recognised learning objectives of science teaching (e.g. AAAS, 1993; Millar & Osborne, 1998; NRC, 2007, 2012, 2013) presses for the establishment of common understanding within the research community as to the exact content of this objective. For instance, this is needed to inform attempts to develop (a) teaching innovations geared towards promoting this learning objective and (b) corresponding assessment approaches and instruments.

Despite the apparent consensus, in broad terms, within science education as to the meaning to be attached to conceptual understanding, it could be argued that the science education research community is still lacking a comprehensive, operational framework for this construct (Ding et al., 2013). This is evidenced, for instance, by the varied approaches that have been reported in research studies purporting to assess students' conceptual understanding. Some examples indicative of this variation are (a) requiring students to apply conceptual tools (e.g. Newton's laws) to unfamiliar situations involving physical systems not studied during instruction (McDermott & Shaffer, 1992), (b) asking students to develop concept maps for a specific domain of interest where to identify the respective core concepts and illustrate how these are interrelated (Lin & Hu, 2003), (c) presenting students with standardised multiple choice tests, such as the force concept inventory (Halloun & Hestenes, 1985), and (d) presenting students with True/False statements drawing on misconceptions illustrated in the science education research literature. We do not mean to imply that any of these approaches is inadequate for assessing conceptual understanding. Neither do we claim that these approaches are incongruent to each other; it might be that they just happen to capture different aspects of conceptual understanding. Our claim is that there is a need to further theorise and parse the construct 'conceptual understanding' so as to articulate the various aspects it may encompass and how they relate to each other.

At a broad level of generality, conceptual understanding seems well-defined. For instance, it would be relatively easy to reach agreement on the position that students who possess operational, sophisticated conceptual understanding should be likely to avoid the non-valid use of technical terms involved in the conceptual tools they are employing (e.g. the misinterpretation of 'R' in the ideal gas law as the radius of some disk) or prevalent conceptual difficulties (e.g. subscribing to the position that the magnetic field is a material substance as opposed to a theoretical, physical quantity). This seeming consensus becomes rather fragile when the discussion shifts towards a finer level of detail that probes the structure and mechanisms associated with conceptual understanding. In particular, it falls short of offering an articulated account of the constituent components of sophisticated conceptual understanding (Ding et al., 2013).

Striving for a robust, operational account of the components comprising conceptual understanding is an inherently complicated task requiring substantial theoretical work. The ideas elaborated in this article could contribute towards this direction by shedding some light onto a specific component of conceptual understanding, namely the epistemic/ontological aspects of the science content knowledge. Clearly, there is a need for additional work to further illuminate this area. One topic that could be usefully addressed relates to the elaboration of the similarities (and differences) in the epistemic value and ontological status of science concepts across different domains of science. In particular, it would be useful to identify specific epistemic and ontological aspects of the content knowledge associated with a reasonably large set of science domains that could be amenable to teaching elaboration in school science. This account could also usefully incorporate a learning progression perspective (Duschl, Maeng, & Sezen, 2011; NRC, 2012) in the sense that it could illustrate how these ideas could become increasingly more sophisticated across grade levels. Embarking on the development and elaboration of such an account could lead to a generic typology of distinct epistemic and ontological aspects that could be brought to bear on different content domains. In addition, it could yield a classification of concepts in terms of the extent, complexity, and abstraction of these aspects. These could offer valuable resources for attempts to develop learning environments geared towards the integration between the substantive side of content knowledge and its associated epistemic underpinnings and ontological considerations.

Another avenue for further research is the development of research-based teaching innovations that could support the integration between the science content knowledge with its epistemic/ontological aspects. Addressing this task posits expanding the currently underdeveloped body of research-based knowledge about students' difficulties and existing resources with respect to the epistemic and ontological aspects of content knowledge in different science domains. Also, it involves experimenting with the enactment of such teaching innovations in classroom settings with the intent to enhance our understanding of learning phenomena that emerge in attempts to engage students in explicit discourse about the epistemic and ontological aspects of content knowledge.

Conclusion

In this article, we have sought to make the case for the need to elevate the attention paid to epistemic/ontological aspects of content knowledge in the science classroom. We have focused on the ideas of ontological status and epistemic value of science concepts as two aspects that could be usefully addressed in secondary science education. We have elaborated on how the inclusion of systematic explicit epistemic discourse, guided by these ideas, could facilitate science learning (i.e. by promoting coherent conceptual understanding, fostering a productive epistemological stance towards science learning, and enhancing students' appreciation of NOS-related ideas). Certainly, this topic cannot be exhausted by this single article. There is a need for further work to better theorise it and we hope that the ideas explored in this article could stimulate further research to explore the role and position of epistemic/ontological considerations in science teaching and learning.

Notes

1. At the highest level of pre-university education, it would make sense to further differentiate between the physical quantities of force and field by recognizing that the first essentially refers to a vector quantity relating to a specific instance of interaction between two magnetic materials, whereas the latter is a vector field, in the sense that it allows generating a vector quantity (such as force) for each different point in the space surrounding a magnetic material (Cassidy et al., 2002).
2. At a more advanced level students could be guided to appreciate that the concept of field was essentially intended to eliminate the idea of "instantaneous action at a distance". It affords interpretations that are local in nature. For instance, if the electric field at a certain position is known, the electric force exerted on a charge located at that specific position can be determined without any knowledge of what happens elsewhere (Bolton, 2006).

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