Science & Education (2019) 28:25–43
https://doi.org/10.1007/s11191-019-00027-3

ARTICLE

Bringing Inferentialism to Science Education

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Published online: 7 February 2019

Abstract
In this article, I introduce Robert Brandom's inferentialism as an alternative to common representational interpretations of constructivism in science education. By turning our attention away from the representational role of conceptual contents and toward the norms governing their use in inferences, we may interpret knowledge as a capacity to engage in a particular form of social activity, the game of giving and asking for reasons. This capacity is not readily reduced to a diagrammatic structure defining the knowledge to be acquired. By considering the application of these ideas to the concept of electrical current and the use of analogies in science education, I hope to illustrate how they may be given practical employment as the child comes to explore *within* the concepts derived from historical scientific endeavours and not merely meander through her individual experiences of scientific phenomena themselves. In moving away from the representational role of analogy, our focus shifts from the quality of the analogy itself toward the quality of the discourse utilising the analogy.

1 Constructivism and Its Critics

Constructivism, as a foundational epistemological theory, drives much of current science education research and many initiatives in teacher education (Matthews 1993; Gil-Pérez et al. 2002). There has been significant criticism both of its philosophical underpinnings and its practical applications in real learning environments (Noddings 1990; Matthews 1993; Ogborn 1997; Mayer 2004; Kirschner et al. 2006). While there is much to be admired in its opening up of the child's-eye perspective and its questioning of the rigid imposition of instructionist methodologies, a naïve interpretation may be prone to lead the science educator to adopt practices which tend to unsteady the knowledge domain as an object of study: the validity of our constructions extends only so far as their viability in describing experience. This may lead to a "relativist ontology" (Osborne 1996, p.59) in which the meaning-making of the child is afforded equal authority to the knowledge of the scientific community. In doing so, we may render much that is of value in the scientific enterprise beyond the grasp of the child.

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Science educators of a pragmatic bent, whatever philosophical stance they may espouse, will adapt their practice to the perceived needs of learners and will not be unduly influenced by foundational theories where these conflict with experience. Many of those working in the science education community are quick to disassociate themselves from more radical constructivist approaches such as that of von Glasersfeld (2001) and reject positions founded only on "personal empirical enquiry" without regard for the "concepts and models of conventional science" (Driver et al. 1994, p. 7). Gil-Pérez et al. (2002, pp. 563–564) explicitly delineated the "ensemble of distortions of the nature of science" rejected by the constructivist tradition in science education, including elements commonly ascribed to it by its critics such as purely inductivist conceptions of science and an inadequate separation of scientific and common-sense modes of reasoning. In doing so, they aim to found their investigations on empirical research on problems encountered in the practical processes of teaching and learning.

But in building our pedagogical practices from no theory, there is a danger that we make ourselves vulnerable to any opinion that is imposed on us from the outside. This is a particular problem for the new teacher who, as yet, has no prior experience with which to arm herself against the pronouncements as to the best practice of often ill-informed external agents. While the science education community itself may reject more radical constructivist positions, it nevertheless finds a voice both in public discussion and educational policy (Matthews 2002, p. 122). On the other hand, the resistance of teachers to the adoption of constructivist approaches (Gil-Pérez et al. 2002, p. 568) may in part be due to a lack of clarity as to precisely what teachers are committing themselves to, thus suggesting the need for a strong metaphor which is able to distinguish the particular approach advocated by science education research. Furthermore, at the very point of our perception of the unfolding educational episode, we may be impressed upon by our prior conceptions as to what constitutes effective learning. The role of a good theory is thus to serve as "a resource for opening up what is currently invisible" (Derry 2017).

Constructivist epistemology describes the child's learning as the construction of a mental model of our scientific conceptualisations, albeit a model of severely reduced complexity (Mayer 1999; Bächtold 2013). Under this representational account, effective teaching is seen as helping the child to draw in her head a diagram encapsulating the spatial, dynamic, and causal characteristics of the domain. The child need not be fully conscious of this internal model, yet it determines her behaviour regarding the use of scientific concepts.

Instead, I propose Robert Brandom's inferentialism as an alternative philosophical foundation for framing discussion of issues in science education (Brandom 1994, 2000). Under this analysis, conceptual and mental contents are best understood not as a diagram, but as a body of norms governing inferential moves and an associated responsiveness to these norms. Knowledge is not an entity, a representation, to be constructed inside the head of the learner but a practical capacity for a particular type of social activity, the *game of giving and asking for reasons*. By avoiding a division between an inner mental realm and an outer realm of nature to be represented, while embedding our linguistic practices in our practical encounters with the world, we recover the notion of objectivity. The aim of education, therefore, should not be the child's construction of a mental model to represent knowledge but her learning how to play a game, to operate within the inferential rules determining it, and, critically, to question the moves of others where they conflict with her own inferential commitments.

My intent here is not to provide a formal argument for Brandom's views, nor to issue concrete prescriptions for pedagogical practice but rather to offer up a new vista from which to consider educational debates. Below, I introduce the core commitments of Brandom's semantic theory and describe its philosophical context. To illustrate these ideas and to explore their potential impact on the practice of science educator and educational researcher alike, I shall then examine how we may understand the teaching and learning of electrical current under an inferentialist paradigm. In doing so, I consider both the inferential role of the concept and the function(s) which representation may have. Central to this is the question as to whether human responsiveness to reasons may be represented. Finally, I shall consider the pedagogical implications particularly as they relate to the use of analogies.

2 Inferentialism and Education

2.1 Brandom's Inferentialism

Constructivist pedagogies explicitly acknowledge the role of education in not only providing information about the world to the child but also in developing her cognitive capacities and, perhaps, in enabling those very characteristics constitutive of the human mind. However, with the spotlight on the child's meaning-making as the locus of learning, one may be worried that there has been a move away from the curriculum as the foundation for education, that is, learning should be learning *of* a body of knowledge. In focussing on the active aspect of learning and recognising that all knowledge must, in being integrated into personal schema, be understood from the particular perspective of each child, there is the potential for loss of traction with the knowledge complexes developed through historical human endeavours (Osborne 1996, 1997; Matthews 2002).

Inferentialism spans the space between, on the one hand, an overly rigid instructionism, accounting for education as the direct transmission of factual content to children, and, on the other, those interpretations of constructivism which risk divorcing the child both from the vault of knowledge carefully constructed over human history and the intransitive world to which it relates. In recent years, inferentialism has been applied in various contexts including the field of education research (Bakker and Derry 2011; Derry 2017; Marabini and Moretti 2017; Noorloos et al. 2017; Schindler et al. 2017; Taylor et al. 2017). Its emphasis on rationality ensures that teaching does not cast the child and her perspective as the sole arbiter in determining the effectiveness of learning. Simultaneously, we remain open to the possibility of growth and change in our communal understanding, assimilating in the very practice of education the contributions of the child to our evolving knowledge of the world.

Central to Brandom's project is an upsetting of traditional beliefs regarding the semantic function of language, particularly the notion that conceptual content should be primarily understood as deriving from the representational role of subsentential expressions. Brandom rejects the representationalist claim that a word "stands for – or represents, or expresses – its meaning" (Peregrin 2014, p. 1). If one begins from the subsentential units (archetypically, individual words and the concepts they represent), the meaning of a sentence necessarily derives from the composition of its parts. An alternative route is to begin from sentences themselves as the fundamental fabric from which meaning emerges and consider the words composing them as carrying meaning only insofar as they contribute to the sentences they appear in. A top-down approach places "whole sentences as prior in the order of explanation to the sort of content that is expressed by subsentential expressions" (Brandom 2000, p. 12). By embracing the inferential capacity of sentences as primary in the order of semantic function, we may nominate the "game of giving and asking for reasons" (pp. 14–15) as the generator of conceptual content. To give a reason requires that one sentence may be used to justify another, which *entails* it.[1] To be able to ask for reasons requires that the claims I make may be challenged and thus are in need of justification (Peregrin 2014, p. 7). My statement that it is raining serves as a reason for my claim that I will get wet if I venture outside. Similarly, you may challenge my assertion as to the state of the weather by noting the absence of clouds in the sky. By the reasons we give, we are each committed to the inferential relations between sentences we are endorsing and are entitled to others. As we play the game and keep track of each other's commitments and entitlements, we may "discover what we are actually entitled to rather than what we, at first glance, assume" (Derry 2017) and thus deepen our understanding of the role that the concepts we utilise play in the inferences we make. By focussing on the inferential relationships between sentences and the social norms governing these, inferentialism enables us to give a fine-grained account of the distinctively human capacity for operating with concepts.

Brandom proposed that we take linguistic expression not as a matter of "transforming what is inner into what is outer but of making explicit what is implicit" (Brandom 2000, p. 8), of "conceptualising it" (p. 16) and thereby delineating the inferential connections. In this context, conceptual knowledge relates to a practical know-how regarding the "inferential practices of producing and consuming reasons" (p. 14), that is, the capacity to explicate our reasons for endorsing particular inferences and to question the inferences of others. To contribute requires that the child be inducted into these practices, creating sufficient points of contact that she is able, as a matter of practical mastery, to perform inferential moves discernible as such to another player within the same knowledge domain.

Simultaneously, we do not lock these concepts to strictly delimited definitions but embed them in a tapestry of cultural processes, explicating their meaning in terms of their role in contributing to the inferential potential of the sentences in which they appear. This potential is not "constituted by the dispositions of individual speakers to draw inferences, but by conceptual *norms* (shared in the linguistic community) that specify which inferences are correct" (Prien 2010, p. 437). Correctness is not a matter of what inferences a particular speaker actually makes or, indeed, is disposed to make. Rather, it relates to how other language users would be expected to behave in response to the inference. In particular, a "correct" inference, unlike an incorrect one, is "immune to certain ways of criticism" (Peregrin 2014, p. 49). Meaning is a matter of the normative rules instituted by the community regarding the correctness of a particular inference and cannot be simply psychologized as the aggregate of personal inferential dispositions. Rather, the rules of the game must be understood as bound up with, but distinct from, the individual moves within it. When I make an assertion, I not only operate with the inferential relations available to me but, through my endorsement; I am engaged in constituting those relations and thus the inferential potentials which lend meaning to conceptual content. Thus, the rules of the game are formulated concurrently with the playing of it. The public nature of this game ensures I am not thereby free to institute new relations without the endorsement of others.

[1] The emphasis here is on how one sentence is *taken* to justify use of another and thus to constitute a valid inference. As discussed in Section 3.1, we are concerned with *material* inferences and not merely inferences valid by virtue of their logical form.

As a matter of practical use, the inferential role of a concept as understood by different language users may overlap sufficiently to enable a referential function for a word. However, the distinctive characteristic of human language is that a word is never *purely* identifiable as the class of entities to which it refers. Given our route to the referential function of words via their role in inferences, the meaning of a word can never stand in isolation from the sentences in which it participates: “noninferential reports must be inferentially articulated” (Brandom 2000, p. 47). My use of the word “cat” distinguishes itself from instances of animal recitation of human language by virtue of its ties to a network of linguistic moves and the associated social contexts necessary for them to count as genuine language use. A parrot may issue the same word in response to the same set of entities but would not recognise any conflict when subsequently using the word “dog” to refer to the very same entities. My use of the word is distinguished from a bestial cry precisely by virtue of its inferential role: given it is a cat, I infer it cannot be a dog.

The richness of these inferential relations furnishes us with the material to move away from flat representational notions of our concepts and to see a space in which to explore them.

2.2 Philosophical Context

Brandom’s approach has some affinity with that of the later Wittgenstein for whom language was not to be thought of as primarily the creation of symbolic forms to represent something external, but as a series of overlapping *language games* encompassing both “language and the actions into which it is woven” (Wittgenstein 1958, p. 5). This conception of meaning as use forms the basis of Brandom’s project. Where he differs from Wittgenstein is in claiming that language “has a center; it is not a motley” (Brandom 2000, p. 14). In particular, he focussed upon what distinguishes our specifically human linguistic capacities, the capacity to give and ask for reasons.

By beginning from the practical employment of language as the foundation of meaning, inferentialism draws upon a rich heritage of pragmatic philosophy that emphasises our interactions with the world and one another and avoids reifying our concepts as something lying wholly outside the practices of individuals and communities. We should see language “as a tool of social interaction rather than an abstract system” (Peregrin 2014, p. 8). However, Brandom’s anthropological account distinguishes itself from many other pragmatic approaches to semantics in his emphasis on normativity and the rules governing our inferences as opposed to our inferential dispositions themselves.

Brandom also endorses a type of semantic holism in that the meaning of a concept depends upon its role in inferences from one sentence to another and thus upon the meaning of all other concepts within the language. As Fodor and Lepore (2001) have noted, this then requires that we explain the capacity of language users to communicate despite the differing inferential significances they ascribe to their respective assertions, that is, the inferences that each is disposed to make. However, Brandom does not understand communication as the transmission of a meaning from my head to one in yours but as a cooperative activity in which we are each able to track the commitments of one another against each other’s respective background of collateral commitments (Brandom 2007, p. 667). The structure of this language game commits us to behaving *as if* we share the same understanding of the concepts we utilise. Where tensions in our understandings become unsupportable, one or both of us is forced to re-examine our background repertoire of inferential commitments. To the extent that our shared language is an historical product of this negotiating process, we can expect that there shall be sufficient overlap to enable a “mapping of [our] doxastic repertoires” onto each other (Prien 2010, p. 443). This moves us from an essentially Cartesian model of communication as the transmission of mental particulars to a Kantian one in which our principle concern is not “our grip on the concepts, but rather their grip on us” (Brandom 2007, p. 669). By building our semantic theory from sentences as opposed to subsentential components, we begin from the smallest unit by which we may express a commitment and thus bind ourselves according to norms. We may then ascribe semantic content to the individual words used by tracking their role in modulating the inferential significance of the sentences in which they appear. This allows for the productivity of language whereby we are able to utilise our finite vocabulary in the construction of innumerable new sentences expressing new content (Brandom 2007, p. 671).

Brandom thus sees pragmatism as extending a move from Kant through Hegel: “Kant reconceives us as normative creatures; Hegel transposes that fundamental Kantian thought into a social key. All normative statuses are in the end social statuses” (Williams and Brandom 2013, p. 372). In this respect, he is in agreement with neopragmatists such as Rorty (1979) who similarly rejected the idea of knowledge as representation of a mind-external world. However, Brandom’s account conceives language as, from the start, intimately entwined with the notions of objectivity and our relation to the natural world. To make sense of our linguistic practice in the game of giving and asking for reasons requires not only that when we use the same terms we share a semantic content but also that the content refers to something persisting externally to the particular dispositions of any individual (Prien 2010). Furthermore, Brandom’s notion of inference spans the gap between purely linguistic utterances and events in the world: in using a concept “one implicitly endorses the propriety of the inference from the concept’s circumstances of appropriate application to its consequences of application” (Brandom 2000, p. 21). In this sense, we encompass also inferences “from situations to claims and from claims to actions” (Peregrin 2014, p. 7). The world imposes itself upon us, moulding the inferential rules by which we operate and thus our scientific concepts avoid “frictionlessly spinning in a void” (McDowell 1994, p. 11). Simultaneously, we are not immutably locked to a single model of the world but admit that all our assertions necessarily come from a particular perspective, a perspective which may have been otherwise.

2.3 Inferentialism in Science Education

In learning science, the child gains access to historically accumulated inferential knowledge channelled through the intransitive aspects of the natural world. The strict division of facts and skills is seen as illusory: to learn a fact is to learn what it entails and hence how to use it. A concept, as a role in the set of inferential moves, has no endpoint at which we can say we now “know” such and such. Rather, we require a suitable environment to be constructed to allow the child to experiment with and test out these new concepts, to explore *inside* them, seeing how they fit with her prior inferential commitments and determining what does or does not follow from what. Learning is a process of adjusting and expanding one’s repertoire of inferences, mutually explicating the inferential moves to which we are each prepared to commit ourselves and thus enabling the practical possibility of doxastic mapping between the child and the teacher who acts as embodiment of the canonical interpretations of scientific knowledge. The task of the teacher is to make apparent the norms governing our concept use, while allowing space for the child to explore and express her own commitments as a mutual understanding is negotiated.

Many of the conclusions drawn from constructivist approaches to science education may be carried into this new method of analysis. It is, for example, obvious that mere rote learning yields only surface knowledge and that we must not neglect the child's-eye perspective in designing educational programmes. But if we accept the primacy of the socially constructed norms governing our inferential moves, developed through our historical engagement with the world, then we must also accept that learning is an inherently social process in which the child comes to be able to operate with our scientific concepts in her discursive practices, questioning the inferential moves of others and explicating her own. Taylor et al. (2017, p. 771) identified two metaphors for learning which have been adopted in the literature: learning as "the acquisition and/or modification of cognitive mechanisms or conceptual structures within one cognitive system" and learning as "a process of becoming a more central or skilled participant in a community". They suggested an alternative inferentialist metaphor of learning as the *mastering* of conceptual content. Mastery, while never fully accomplished, may be approached as an individual develops her capacity to apply concepts in her inferential reasoning and yet is "underpinned by participatory interaction between the players of the game of giving and asking for reasons" (ibid, p. 779). In this way, we may synthesise the cognitive and social dimensions under a single metaphor.

3 An Illustration: Teaching and Learning Electrical Current

3.1 The Inferential Role of the Current Concept

Let us now illustrate the application of these ideas to education by considering the concept of electrical current. If one has grasped the concept, what inferential roles would one be able to ascribe to it, that is, what inferences would one be able to make that utilise it? Consider a simple proposition making use of the current concept: "There is a current in this circuit". The inferential role of the concept (insofar as it relates to this particular proposition) is determined by the inferences it is appropriate for us to make.[2] By stating this proposition, we are committing ourselves to certain other propositions: "There is a movement of electrical charge in this circuit"; "This circuit is made from a conductor"; "An ammeter connected to the circuit will register a non-zero reading"; "I may feel a shock if I touch the circuit"; "There is an emf source in the circuit"; "The circuit will become hot"; and so on. Of course, one may not be inclined to draw all such conclusions: the child who has yet to learn about ammeters is accordingly limited in the scope of her commitments. But this is simply to say that her conceptual knowledge is, as yet, incomplete. More interestingly, each of these conclusions (with perhaps the exception of the first) is defeasible: we may find grounds for disbelieving it despite our commitment to the original proposition. Perhaps my ammeter is not sensitive enough to detect the current. Perhaps the emf is induced by a magnetic field. Or perhaps the circuit is made from a superconducting material thus requiring no emf source to maintain a current. To draw each of these conclusions from our original proposition requires what Sellars (1953) termed a *material* inference remaining always open to revision in the light of collateral premises brought to bear. What is significant, however, is that my lack of commitment to any of these inferences calls out for an explanation, for my provision of a *reason*. Similarly, if in

[2] Technically, it also depends upon what propositions it is appropriate to draw this inference from, but we shall keep our analysis simple.

conversation with another person it transpires that they are not inclined to draw these inferences then, in the absence of any extraneous factors of which I am aware, I should be inclined to request some reasons from them. I may not, as a matter of fact, actually make such a request but if I am not at least disposed to pose the question to myself, it is dubious whether I truly appreciate the relevant concepts at hand.

Furthermore, we are concerned here not only with the kind of intra-linguistic inferences above but with the physical manifestations in our behaviours. Thus, if I insist on asserting the presence of an electrical current while my ammeter indicates no evidence for this and I attempt to fix the circuit then, given my lack of comment on this discrepancy between my words and my actions, I must expect that others may ask me to justify my behaviour by providing suitable reasons. The inferential role of the current concept is determined not merely by the appropriate movement from one linguistic expression to another, but by moves between expressions and physical actions as one manipulates the apparatus and, indeed, between different physical actions (though the scope of such inferential behaviour unmediated by language is severely limited). It would thus be incorrect to say that the handyman, who skilfully manipulates complex circuits but does not possess the relevant vocabulary to express his inferences in direct linguistic form, is lacking the relevant conceptual knowledge while the student, able to answer the most difficult of exam questions but not applying these in his practical manipulations, possesses it. It is true that, without the linguistic capacity to manipulate the concepts in a more abstracted way, the handyman will be limited in his capacity to explicate his own reasoning and to absorb new ideas. However, *both* handyman and student can be said to be limited in their inferential capacity.

Finally, it is evident that the capacity to operate with these inferences requires access to an extensive array of concepts such as "charge", "conductor" and "emf". Thus, if we are to equate the content of our current concept with its inferential role, we must understand this content as both determined by and determining the content of other related concepts. The introduction of a new concept to one's vocabulary is always within a conceptual context shaped by the background social practices of language users. In turn, by introducing this new concept, the context is itself modified as previously held concepts are reconfigured to accommodate this new knowledge.

3.2 What Is the Role of Representation?

Having outlined the kinds of inferences with which we are concerned, let us turn to the distinctions between our different accounts of conceptual content. Under a representationalist understanding, we would take it that there is a concept of electrical current that needs to be constructed in order to utilise it in the kind of inferences above. However, the inferentialist account turns this on its head and claims that possession of the concept *just is* the commitment to such inferential moves and, with them, the associated second-order behaviours with regard to the moves of others. As such, the notion that there is an entity, the current concept which one must construct in one's head over and above the relevant inferential moves becomes superfluous. That I will commit myself (given the appropriate context and in the absence of extraneous factors) to such inferences and that I am able to explicate my reasons for such commitments and question the commitments of others is the necessary and sufficient condition for my possession of the concept.

To motivate this interpretation, consider the problems trying to delineate the content of the current concept in a way which does not ultimately reduce to these inferential behaviours. We may, perhaps, take it that the relevant concept is something like a mental picture of a flow of charged particles. And yet this, in and of itself, does not yield all the content for the concept that we desire. For example, it says nothing of the necessity for a conducting material and, what is more, is prone to the *mis*conception that current will escape from an unplugged socket (Harrison and Treagust 2006, p. 14). Furthermore, if a student in possession of a different mental picture, perhaps one conforming more closely to the quantum account, is able to make *all* of the same inferences, then would we really argue that she lacks the relevant concept?

The representationalist has yet two further lines of argument to which she may appeal. The first is that, while the content of a concept is essentially determined by its inferential articulation, in practice, it may be useful (perhaps indispensable) to have some clear representation of the current concept in one's head. This view is not really at odds with the inferential account of semantics, but perhaps undermines the educational value of introducing the account. Below, we shall illustrate how some useful insights into education are indeed made available by considering the inferential view of conceptual meaning.

The second avenue open is to argue that the set of norm-governed moves determining the inferential role, and thus the content, of a concept is itself best understood as "represented" in the head of the learner. What is constructed in learning, then, is something akin to a diagram in one's head which represents the conceptual knowledge in question, i.e. the appropriate inferential moves utilising the concept. Indeed, this is what we have begun to do by listing some such inferences above. But is it possible, or indeed useful, to understand responsiveness to these inferential norms as represented in the mind?

3.3 Can Responsiveness Be Represented?

How feasible is it for us to represent such inferential commitments in a closed form, that is, for us to draw a diagram capturing all relevant inferences such that it can be applied without further insight? If we can do so, then it should be possible, at least in theory, to provide a student with no prior training in these scientific concepts with such a diagram and for them to use it algorithmically to solve any relevant problem. What learning then amounts to is helping the child internalise this so that they can take in input data (the problem presented), run it through the diagram and determine a solution. Doubtless, our means of assisting them in this will not be to simply present them with a comprehensive representation and ask them to memorise it, but the end result may not be so different. The purpose of such a mental map is to capture in advance the relations between certain behaviours (both intra- and extra-linguistic), which are held appropriate by the community. Once acquired, this may then determine subsequent inferential behaviours.

But if it happens that we cannot define in advance all the myriad contexts and inferences to which we may be exposed then does such a diagrammatic understanding present us with something useful? That is, if we cannot actually draw the representative diagram then is there a benefit in claiming that a hypothetical diagram represents the knowledge? If the set of inferential moves and contexts in which they are made is uncountable and, furthermore, is irreducible to a finite mechanism by which they may be generated then do we gain by understanding our concepts as static entities to be constructed? Even if we do believe that, in theory, they should be reducible to a tractable set then we would require that we actually can, in practice, perform this reduction in order that this account is made useful.

The obvious rebuttal is to suggest that we can and indeed do appeal to diagrams encoding the relevant relationships between concepts. Numerous studies have demonstrated the effectiveness of concept maps both as a tool for the retention of knowledge and for the transfer of knowledge to new scenarios (Nesbit and Adesope 2006). However, while such concept maps can be used to good effect, few educators would presume they are sufficient *by themselves* to convey the requisite ideas to learners without some element of interpretation and of activity utilising them. Thus, Novak and Cañas (2007) proposed student involvement in map construction and advocated the use of the concept map as an artefact around which other learning activities may revolve. Nesbit and Adesope (2006) similarly noted the demonstrated importance of how maps are used to the effectiveness of knowledge retention. Thus, we cannot expect to be able to present a map to the child and for it to be automatically internalised and applied. In short, it must be *understood*. Is this merely due to the practical difficulties in, for example, constructing a sufficiently detailed map to capture all the required conceptual connections while maintaining the learner's attention? Or is there also something at fault with our above account of the end result, that is, of what it is to possess the relevant conceptual knowledge?

Consider our second inference above: an electrical current implies that the circuit is made from a conducting material. For the child to make sense of this, we may introduce her to the distinction between conductors and insulators and in doing so, we may refer to metals. A possible inference by the child is therefore that an electrical current implies a circuit formed of a hard, shiny material. While this is by no means a certain conclusion, it is a potentially valid (and perhaps useful) inferential move in the correct circumstance and thus should presumably already appear on our complete list of inferences constituting the current concept. And yet, we constructed this by appealing to other knowledge domains and to the child's own informal understanding of metals (and even of materials).

A more graphic example is furnished by the concept of force. To understand the concept is not merely to delineate it in terms of its function in the equations of classical mechanics, but to appropriately assimilate it into one's intuitive comprehension of the physical world and thus enable effective interpretation of those equations. We may, of course, need to adjust our intuitions in order to accommodate this new scientific perspective. But without this substratum, the concept is hollow as we are unable to bring into play the kind of bodily experiential knowledge enabling our inferential actions. When introduced to the concept in the classroom, the child must be able to draw on her prior experiences of forces—not simply the word but the understanding of *what it is* to be caused to move—for this movement to be in *this* or *that* direction. When multiple forces are combined, she can imagine how it *feels* while her teacher may assist through physical demonstration. Doubtless, these intuitions must be adapted to the formal scientific definitions to which she is introduced (for example, a force is not required for movement but only for acceleration). However, they should not be seen as an obstacle to be overcome but rather as the substance from which her understanding must be sculpted.

The meaning of the concept is thus determined by an inferential role that encompasses both the strict definitional rules we choose to apply and the mass of intuitions derived from physical experience of the world. To be able to operate with the concept requires both this more intuitive aspect and an immersion in the scientific discourse utilising it, the content arising at the intersection.[3] In the context of education, it is far from clear that learning occurs merely in the acquisition of some definitional content and that this intuitive aspect may be considered mere background. If we institute this division too early, we risk obscuring the learner's

[3] There is some similarity here to Vygotsky's account of the development of spontaneous and non-spontaneous concepts as parts of a single process (Vygotsky 1939; Derry 2008, 2013).

difficulties in interpreting the new content. What may be required is an examination of her pre-existing inferential commitments in order to shift her intuitions appropriately to accommodate this new knowledge. Indeed, grasping the content of any concept we choose to represent may require the learner to modify a broad range of inferential commitments. It is these commitments which determine the meaning of the concept and it is thus difficult to define which inferences should be thought to constitute the concept and which ones are merely backgrounds required to interpret it appropriately. If experienced users agree as to the inferences central to composing a concept or set of concepts, then this is largely a result of their already sharing similar background commitments. We cannot assume such a shared background for new learners. Thus, any attempt to impose a centre upon a concept is necessarily somewhat arbitrary and relative to the context of employment.

When we construct a representation of our concepts, does it merely define the pre-existent rules determining our operations or is it rather a newly imagined abstraction from an integrated mass of normative dispositions? If the latter, then the teacher's role in explicating conceptual content is akin to the artist's in putting brush to canvas: the strokes produced serve to represent the object considered but do not *wholly* do so. Her choice of contours traced is constrained by that represented but not decided by that. Rather, the teacher must integrate her understanding of the object of study with a sensitivity to her learners and the understandings they have expressed in the course of their learning. The choice of which inferences to explicate is driven not so much by their centrality in constituting the relevant conceptual content (whatever this would mean) but by their potential effects upon the learners as intuited by the teacher through her understanding of the shared commitments behind the educational episode. Attempts to diagrammatize conceptual content may accumulate ever greater detail and yet what we are achieving is only a drawing of the edges. The representation takes on significance only when we manipulate the content inside this outline, thus requiring an active act of interpretation, of filling-in. In this sense, I suggest that it is appropriate to consider conceptual content as determined by a *body* of norms: while we may tweeze apart the fibrils constituting our normative commitments, this body may never be fully decomposed to a finite inventory of inferential moves. The act of representation, as a form of explication, may shift our own perceptions of propriety regarding certain conceptual manipulations but our perception is never reducible to such representation.

This rejection of the static structural notion of conceptual content is prone to objections that the attunement of the learner to a potential infinitude of inferential commitments makes the learning process mysterious: how, in a finite number of learning events, are we to acquire such a boundless array of communally shared rules regarding our inferential behaviour? We may escape this quandary by noting that each learning event has the capacity to propagate throughout our system of commitments. Consider our above list of inferences from the statement “there is a current in this circuit”. If I am inclined to each inference but the last (that a current will cause a circuit to become hot) then upon learning this, I gain not only this inferential move but many others based upon my prior commitments. For example, I am now aware that an ammeter with a non-zero reading is likely associated with the temperature of the wires increasing. If we extend our list of inferential commitments further, then each new inferential move acquired brings not only itself but a potential infinitude of new moves, thus scaling with the breadth of commitments composing our communally shared conceptual content. The extent of propagation through my system of inferential commitments, and thus the impact upon my behaviour with regard to concept use, marks the depth of my learning of the new inferential move. This propagation need not occur *internally* to my mind but rather displays itself in the complex shift in my potential responses to hypothetical future scenarios in which I may find myself. The change to my internal state may be quite simple while yielding radical transformations in my subsequent behaviour by virtue of the manifold entanglements of my new inferential commitment with others. In this sense, even the most trivial information has a potentially profound impact. Indeed, it is this potential for unattenuated propagation which lends the transformative character to educational experiences. By casting conceptual content as a determinate structure to be represented in the mind of the learner, we may limit this propagative capacity.

4 Implications for Pedagogy: The Use of Analogies

4.1 Analogies and Mental Models

Established constructivist epistemology, interpreted under a representationalist paradigm, characterises the child's learning as the construction of a mental model of the canonical conceptualisations of scientists (Mayer 1999). This model, then, is something akin to a diagram in the child's head which captures the relevant characteristics of the knowledge domain. To be able to draw the appropriate inferences, characterising the conceptual content requires that the child first constructs such a model. The question then becomes how we enable the child to make such a construction.

A common means employed is the use of analogies. Analogies are frequently applied in scientific reasoning (Dunbar 2001; Coll et al. 2005). To be of use, an appropriate analogy from base domain (or source) to target domain (that which is to be explained) must be chosen. Hesse (1966) suggested three criteria for acceptable analogies: there should be observable similarities between the domains, there should be the potential for carry-over of (at least some) causal relations from the source to the target (thus enabling inference) and there should be no essential differences impeding the capacity to draw valid inferences. In the context of education, the effectiveness of analogies in advancing student knowledge and understanding of science has found wide agreement (Coll et al. 2005; Niebert et al. 2012; Haglund 2013).

However, the effective use of an analogy requires that the learner is able to make the distinction between surface similarities and genuine structural features in common. Gentner (1983, 1989) analysed this in terms of the mapping of relations between objects from the base domain to the target domain. In this mapping, greater weight is afforded to mapping higher-order relations (such as the causal relationship between two object-relation statements within each domain) while discarding the attributes of the objects themselves. This structure-mapping theory thus allows us to distinguish effective analogy use from mere statements of similarity. Blanchette and Dunbar (2000) have demonstrated differences in attention to the structural depth of analogies depending upon the task being addressed. In particular, subjects were found to focus upon superficial similarity when asked to retrieve source analogies from a set previously presented to them, but gave greater attention to deep structural features when tasked with generating their own analogies. This emphasises the importance of learner engagement with analogies, discussing and critiquing those of others while constructing their own (Abell and Roth 1995; Coll et al. 2005).

One common analogy for electrical current is the flow of water driven by a pump around a "circuit" of pipes (Schwedes and Dudeck 1996; Heywood and Parker 2009; Gentner and Gentner 2014). Adopting a representationalist perspective, the analogy is effective insofar as it is able to act as a template for the learner's construction of a mental model, an internal diagram representing the relevant conceptual content. This allows them to "find and visualise connections between a newly taught context and what they already know" (Harrison and Treagust 2006, p. 12). The imperfect structural match between the source and the target may require that the learner modifies her initial model and builds upon the analogy in response to feedback. Through this process, her mental model may gradually come to mirror the targeted domain. In subsequent engagement with this domain, she may then refer to and utilise this extended model to guide her interaction, understanding, for example, that a current is associated with some kind of movement around the circuit and yet that the behaviour will not precisely match that of the water pipe, for example, electrical current will not "leak out" from an unattached wire.

4.2 Inferentialism and Analogies

Under an inferentialist interpretation, there is no diagram inside the learner's head which represents the requisite knowledge; therefore, the function of an analogy cannot be to modify such a diagram. If we understand the inferences to which the learner is committed to be represented internally, then, as she gains knowledge, any modification brought about by the analogy must be propagated through the chain of inferences represented *inside* the learner. But if we understand her knowledge as a matter of her *potential responses*, then this propagation is not internal to the learner, but occurs through the possible future interactions she may have with her external social and physical environment. Thus, as discussed in Section 3.3, this may lead to an alteration of her internal state whose individuating features, while causally related to her subsequent inferential dispositions, bear little resemblance to them. Our earlier discussion indicated that the inferential moves she may be called upon to make, even within a particular knowledge domain, may involve immense contextual subtlety in their application requiring an intractably large set of context-sensitive inferences to characterise the knowledge of the expert. Given the difficulty in finding a structural form which captures this body of inferential norms, it may be more appropriate to characterise the knowledge to be gained not as an entity to be represented but as a capacity for a particular type of social activity within the knowledge domain, the giving and asking for reasons. The objective, therefore, is not the construction of a mental model to represent knowledge but learning how to play the game of electrical circuits. To play the game is to operate within the rules determining it, to make inferential moves according to our understanding and to question others where their moves conflict with our own commitments, that is, to ask for reasons.

As such, the usefulness of an analogy is found not so much in its capacity to assist the child in constructing a mental model but in its potential for inspiring suitable norm-governed behaviour regarding the target domain. Its strength thus lies as much in its affective potency in taking hold of the child and turning her toward particular ways of using the scientific concepts as in any abstract structural similarity to these concepts. This seems in accord with Harrison's (2006) emphasis on the affective dimension of analogy use and Heywood's (2002, p. 233) call to "shift focus from determining the effectiveness of analogy in cognitive transfer from base to target domains towards the recognition of the role of analogy in generating engagement in the learning process". However, we are going further in taking the child's knowledge to be *composed* of her dispositional attitudes thus synthesising the cognitive and affective dimensions. The point is not that we must capture the child's interest *in order* to enable her effective construction of a mental model but that knowledge itself is made up of the normative attitudes which the child adopts, attitudes which we may hope to inspire through the appropriate use of analogies. Knowledge, now understood as a practical competency in operating with our concepts, depends as much upon one's affective posture with regard to their use as upon an abstract notion of how one *should* use them. Thus, "knowledge-how is a concept logically prior to the concept of knowledge-that" (Ryle 1945, pp. 4–5). My "knowing" the processes to be applied in riding a bicycle does not sum to my capacity to actually do so. This requires also my disposition to faithfully carry these processes through in the appropriate manner. Under an inferentialist interpretation, it is this capacity which is the primary constituent of my knowledge and not the abstraction to a list of processes extracted from it.

In this analysis, the structural similarity of the source seems less critical. Indeed, the notion of structural similarity seems artificial given the need to select, somewhat arbitrarily, which inferential commitments are most critical to the composition of the concepts learnt. Rather, educators will select analogies on the basis of their potential to appropriately shift the learner's behaviour in utilising the concepts. In making such a choice, the teacher does not so much compare the respective list of inferences associated with source and target but operates globally upon her integrated understanding of learners and the material to be learnt. An analogy that works well for one particular teacher and for one particular class may fail for another (Harrison and Treagust 2006, p. 13). Much as the conceptual content itself may not be easily delineated, the operations of the teacher in determining her educational interventions are not reducible to "practitioner-proof" practice (Dunne 2005, p. 375) but require her exercise of good judgement developed through her prior teaching experience and through her probing of learners' inferential commitments.

While we aim for our analogies to possess sufficient conceptual overlap to enable useful comparison, deviations may themselves be a point from which we may push-off into further discussion. The analogy brings something to the lesson more by virtue of the discourse it generates than by the "degree of match" (Aubusson et al. 2006, p. 6). Thus, divergence of the analogy from canonical conceptualisations may itself provide a locus around which debate may centre, a debate which, ironically, may be missed were we to introduce instead an analogy not leading to this misconception. Where an analogy may be adopted too readily, it "resonates so closely with the learner's existing experience that transfer from the base domain to the target domain is considered intrinsically coherent and engagement with the synthesis of ideas that relate to the phenomenon is closed down" (Heywood 2002, p. 240). By moving away from representations, we emphasise the quality of classroom discourse centred upon the analogy over the quality of the analogy itself for the analogy lacks any force unless it is actually implemented in reasoning: "meaning in science is, quite literally, generated in discourse and does not reside independent of it" (p. 236).

If we understand the learning of electrical circuits as induction into a game, then the need to engage in playing this game finds new significance, for the game comprises not only familiarity with the moves permitted but also with how we respond to one another. Thus, when the child questions her peer's notion of leaky wires, she is not only engaged in moulding her conception of electrical current but she is also developing the practical knowledge of how to go about giving and asking for another's reasons within this game. That the appropriate forms of questioning may be specific to the knowledge domain permits us to categorise it as a component of the game of electrical circuits as distinct from a generic reasoning capacity. This ability to respond to a dynamic discourse is itself a part of what it means to understand electrical circuits. Her discursive capacity thus moves from a mechanism to construct a static mental model to a component of her knowledge itself. Thus, pedagogical efforts to engage students in debate regarding the uses and limitations of our water pipe analogy are not a means toward acquisition of a more fully evolved mental model but rather allow the exercise of a domain-specific reasoning capacity itself constituting the knowledge gained.

4.3 Shifting Perspectives

While an inferentialist epistemology does not directly dictate prescriptions for pedagogical practice, it does motivate a new perspective on matters of educational interest. In particular, it may allow us to preserve the constructivist focus on the child and her understanding while avoiding erosion of the knowledge domain under study (Derry 2017). Constructivist accounts of learners' meaning-making have in common with instruction-focused pedagogies a notion of the child looking out at the world and building a mental model to reflect it. Thus, the child begins from a state standing apart from her environment and in need of connection. By contrast, inferentialism begins from the child embedded in her social and physical habitat and engaged in an ongoing communal activity of articulation of our inferential commitments. This externalist account shifts the focus from the construction of internal mental models toward the "actual doings and reasoning" of the child as she progresses toward mastery of the knowledge domain (Schindler et al. 2017, p. 473).

Adopting this perspective suggests several conclusions of relevance to the employment of analogies in teaching and learning. First, by reattuning the learner's attention from the structural similarity of source and target to her own engagement in the social activity of exchanging reasons, we may open up possibilities for how and what analogies are applied. In particular, our emphasis changes to the capacity of an analogy to latch onto the learner's prior experiences and draw out her inferential commitments into the classroom for consideration and debate, not as something to be overcome but as something to be mutually negotiated in the game of reasons. The importance of the affective dimension of analogy and its ability to draw the learner into discussion flows naturally from an inferentialist view of learning. Furthermore, we may place greater stress on the learner's capacity to "switch perspectives" (Schindler et al., p. 489) as she learns to operate with multiple analogies. By playing down the importance of constructing any particular mental representation, we instead embed the analogies in an ongoing dialogue. It is the dialogue which acts as a fulcrum for the child's learning and not the analogies themselves. We may hope that by thus shifting the focus, we address the difficulties children may have in operating with multiple analogies simultaneously (Harrison and Treagust 2006, p. 18), while we maintain the flexibility of conceptualisation characteristic of deeper learning.

Second, the analogy used is seen as a transitory aspect of knowledge, useful insofar as it primes the appropriate responsiveness when operating within the knowledge domain. Thus, once I have mastered a concept, I no longer need to appeal to an unconscious representation built from this analogy, but I am simply inclined toward the appropriate inferential commitments: the representation drops out of the picture. It is only when I encounter difficulties that I must once again employ representations to clarify my understanding. When I am told that a second battery is added to a circuit, I am instinctively inclined to respond that the current will (other things being equal) increase. I know this not because I appeal to an unconscious construct, an analogous picture in my head of how the circuit behaves, but simply because this is the response to which I am disposed, primed by my previous encounters with such conceptual content. It is only when presented with a novel scenario that I need to construct from my inferential commitments a model matched to the problem at hand to bring these commitments into contact with one another, exposing their conflict or accordance. And once I have acquired the new inferential moves enabled by this encounter, I may again dispose of my mental representation.

This brings us to our third point. Given that an analogy may serve as a kind of explication, we may also describe the capacity to give and ask for reasons as a capacity to respond to and generate new analogies. The distinction here is that what is to be acquired is not a representation at the end of learning to be appealed to in solving problems, but the capacity to construct a new model and to appropriately manipulate it according to the particular demands that emerge. If learning is to be more than rote memorisation of inferential rules, then the learner must be enabled to engage with novel combinations of concepts. To operate appropriately with these not only requires that she be inclined toward the appropriate inferences but also that she be able to capture these in a form suited to the task at hand. She needs to be able to encode her understanding (or rather the immediately relevant components of it) in a newly constructed model which conforms to the question appropriately to make apparent the inferences. A model is not pre-constructed to store inferential commitments ready to carry into an exam, but constructed in situ *from* inferential commitments already held in order to provide a tool for manipulation. This may explain the observed utility of students seeking their own means of modelling requisite inferential features of a domain through analogies (Abell and Roth 1995; Pittman 1999). Much as new teachers often claim to have understood an idea only once they have been required to find ways to explain it, so the child's understanding is in her capacity to find new means of explication. Thus, our attention turns from providing the learner with a comprehensive model representing the inferential knowledge to enabling the learner to build her own models, to find new analogies and select those appropriate to the task at hand. The learning is in the exercise of the capacity to construct and deconstruct models not in instruction in any single model. Table 1 summarises the contrasting epistemological and pedagogical positions of inferentialism and common representational accounts of constructivism.

5 Conclusion

Inferentialism offers an innovative approach to understanding the teaching and learning of science. It shares with constructivist theories a commitment to the careful cultivation of the child's scientific understanding, that is, that the material learnt should be made meaningful to them. However, such meaningfulness is not understood as a matter of individual satisfaction but rather must be judged in the context of the social norms instituted in the domain and derived from historical scientific endeavours. Thus, it is not sufficient that the child engages in an individual activity of sense-making regarding her experience of "science-things". Rather, the content of scientific concepts is best understood as bound up in their inferential role within the community's discourse, filtered through the natural world. The mind's tendency to represent to itself its own knowledge in compact symbolic form may lead one to presume that such a form adequately captures the requisite inferential commitments composing this knowledge. And yet adequate representation is achieved only from the perspective of one already in possession of the relevant commitments: what is to count as adequate is a function of who it is who is interpreting the representation. Thus, the body of normative rules determining conceptual content is not easily reducible to diagrammatic form. To acquire an appreciation of these concepts requires that the child be engaged in an exploration of their inferential roles, but an exploration mediated by the active and ongoing input of the teacher as the embodiment of canonical interpretations of scientific knowledge.

Table 1 A comparison of the epistemological positions and pedagogical implications of inferentialism and constructivism interpreted under a representational paradigm

Constructivist pedagogy	Inferentialist pedagogy
Learning relates to a canonical conceptual structure characterising the knowledge domain.	Learning relates to a norm governed game of giving and asking for reasons within the knowledge domain.
Knowledge is understood as an entity, a structure the mental representation of which is acquired through a variety of individual and communal activities.	Knowledge is understood as a capacity to engage in a particular form of social activity acquired through appropriate practice and irreducible to a structure defining it.
Learning is dynamic but knowledge to be gained is imagined as either a static and stable object constructed and shared by the community or else as being wholly relative to the individual.	Knowledge itself is viewed as a dynamic discourse between individuals according to socially determined norms governing the game and filtered through the natural world.
The objective of an analogy is to assist the learner in constructing a mental model representing the canonical conceptual structure.	Analogies may help to instil behaviours (including second-order behaviours toward others) and attitudes which conform to the norms governing the game.
Analogies are typically valued according to their structural similarity to the canonical conceptualisation.	Analogies are valued according to their usefulness in motivating appropriate behaviours and attitudes regarding concept use.
The focus of pedagogy is acquisition of a mental model using the analogy as a template and discussion as a means to modify this model in the direction of the canonical conceptualisation.	Pedagogy is focussed upon mastering the capacity to question others' reasoning within the domain and respond to the questioning of others, utilising the analogy as a point for discussion.
Pedagogy is open to the free exploration of the learner across the topic but has a closed conception of the targeted knowledge to be gained.	Pedagogy may limit the learner to exploration utilising the relevant concepts but has no end objective such that learning of the domain can be said to have been completed.

This fresh theoretical approach illustrates the potential to shed new light on issues of relevance to current educational research. Adopting this new understanding may allow us to reframe the insights derived from traditional constructivist analyses. By doing so, we place a greater emphasis on the child's engagement with the normative rules governing concept use. This highlights the need for the careful design of learning tasks to not only engage children with the materials of science but with the modes of discourse characterising scientific domains.

Acknowledgments I would like to thank Professor Jan Derry for introducing me to many of the ideas discussed in this article and for her invaluable assistance in its preparation.

Compliance with Ethical Standards

Conflict of Interest The author declares no conflict of interest.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

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