THE COMPLEXITY OF SCIENTIFIC CONCEPTS: THE GOOD AND BAD NEWS FOR EDUCATORS

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Abstract

This paper begins by stating some assumptions about scientific concepts and learning difficulties that educators often make. It then describes how scientific concepts are seen from the perspective of the field of cognitive science and the research field of science education. The view from these fields suggests that scientific concepts are complex structures made up of a number of different types of knowledge elements. The paper then turns to commenting on an aspect of this complexity that can be used by educators, namely that many of the knowledge elements that make up scientific concepts are available to leaners. Thus, the good news is that instruction can build on these resources. The bad news, however, is that coordinating these multiple resources to support scientific understanding is challenging. The paper concludes by pointing out that some progress is being made in science education research to identify ways to teach with this complexity of scientific concepts in mind.

Introduction

When science educators use the word "concept," they often have some kind of qualitative or quantitative definition in mind. At the elementary (primary) level the concept of matter might be characterized in terms of its definition – *Matter is that which has weight and occupies space.* At more advanced levels a quantitative definition for a concept might be provided – e.g. $Kinetic\ Energy = \frac{1}{2} mv^2$ or $F = ma$. Traditional instruction would typically introduce the definitions, present a few examples and then encourage application to other situations or problems. Laboratory experiences would often be designed to verify the accuracy of relationships expressed in the definition – e.g. relationships between variables. More progressive instruction might begin with hands on experiences so that a verbally expressed definition is only introduced after the learner has the relevant concrete experiences. At more advanced levels, the experiences may result in the opportunity to infer the relationship between variables.

When the usual instructional approaches are not successful, educators have to diagnose the difficulties faced by students when trying to make sense of scientific concepts. A ready diagnosis is that scientific concepts are "abstract". Used in this context, "abstract" can mean *removed from everyday experience* and/or *expressed in an unfamiliar language* (including mathematics). When the difficulty that students face is diagnosed as the abstract nature of scientific concepts, the implication for instruction is often thought of in terms of *readiness*. It might be said that younger learners are "not yet ready for abstract concepts". This is an unfortunate legacy of Piaget's stage theory of cognitive development. But Piaget's theory has, for some time, been shown to underestimate the thinking of younger children (Carey, 1985).

In this paper, I describe how scientific concepts are understood from the perspectives of the field of cognitive science and the research field of science education. I explain what researchers in these fields have in mind when they use the phrase "the concept of ..." As I will explain, the picture of concepts we get from these fields is of a fairly complex cognitive phenomenon. It is this complexity that is the source of the challenges of teaching and learning. However, the complexity of scientific concepts can be broken down into components that, when isolated, can often be shown to be readily available to the learner. The challenge, therefore, ends up being that of assembling diverse knowledge elements.

Scientific Concepts from the Perspectives of Cognitive Science and Research in Science Education

Researchers in the fields of cognitive science and science education have a different understanding of what they mean by the word "concept" when compared to that of most educators. While there are in fact a variety of different views of concepts in these fields, this paper is not the place for an extended discussion of these differences. Instead, the purpose of this section is to illustrate two prominent views - one from cognitive science and the other from science education – which give a single overall picture of concepts around which there is substantial consensus. I begin with cognitive science.

The cognitive developmental psychologist Susan Carey (2009) has formulated an explicit account of the nature of concepts as follows. To her, a concept is a symbol in the mind that supports the ability to think (e.g. categorize, reason, solve problems) and use language. In her view, a concept is a mental representation (some mental symbol) that *refers* to a class of things in the world and participates in a system of inferences. In Carey’s use of the term, a concept *itself* is simply some symbol or mental token, its *content* is characterized by the set of things in the world to which it refers *and* that system of inferences it participates in. Together these aspects of the content of a concept will support distinct judgements about distinct kinds of things in the world and will enable reasoning and problem solving about these distinct kinds. Concepts will also enable language use because they represent the meaning of words. Figure 1 represents this graphically. In the figure, some generic concept (C) is seen as referring to some subset of objects in the world (O6 – O8) and participating in a set of propositions relating it to other concepts (A, D & P). One way to think about the set of propositions that determine the inferential aspect of the content of concept is to imagine not knowing a language and using a dictionary in the language to characterize the meaning of a word.

In science education researchers are converging on a consensus view of concepts that is in many respects consistent with the view from cognitive science just described. Researchers in science education increasingly think of concepts in terms of a mental “ecology” with many interacting components (see Amin, Smith, & Wiser, 2014 for review). These components include domain specific beliefs formulated in language or mathematics (DSB); metacognitive and epistemological beliefs *about* knowledge and learning (MEB); imagery, image schemas and mental models that are iconic representations (IR). Learning a concept from this perspective involves in part acquiring more components and in part (a large part!) reorganizing those components. To illustrate these different types of knowledge components (indicated by the relevant acronyms in parentheses) let’s use a description of elements of a fairly (yet not very sophisticated) scientific understanding of the concept of matter (see Figure 2) based on Smith and Wiser (2013).

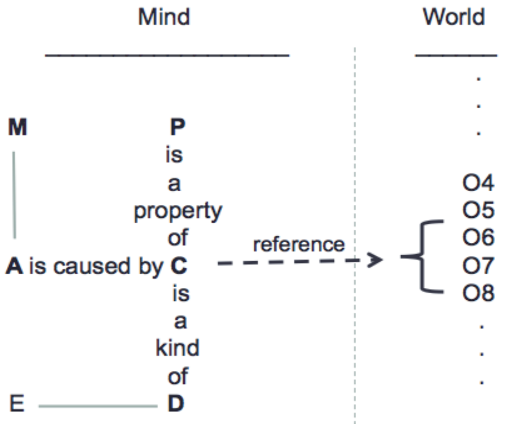
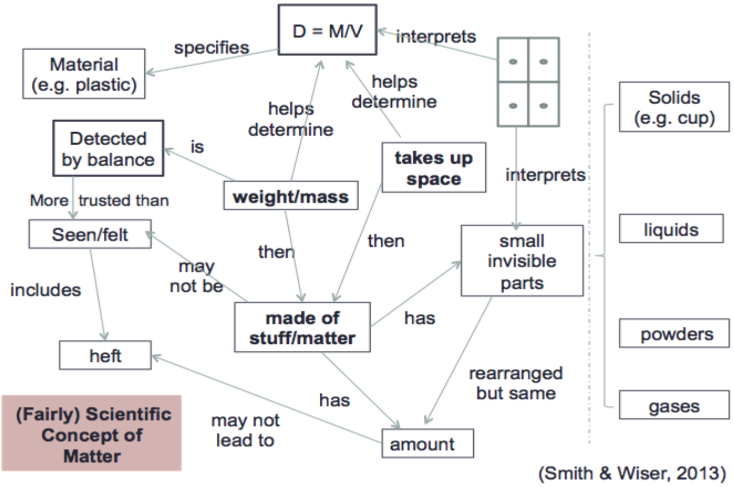


Figure 1: An illustrative representation of concepts.



(Smith & Wiser, 2013)

Figure 2: A representation of the content of a fairly scientific concept of matter.

The content of the concept of matter represented in Figure 2 can be summarized as follows. Something is considered to be made of matter if it has weight and takes up space (DSB). That matter/stuff can be visualized as composed of very many small invisible parts (IR). These parts can get rearranged and form different shapes and take different forms (solid, liquid, or gas) (DSB). Sometimes very small amounts are not visible or felt but we know that they can be detected using a sensitive weighing scale and this indicates their presence (MEB). Different materials consist of matter that is packed to different degrees in a certain space (DSB). That is, the density of the material can vary. We can quantify these ideas through the definition of density as mass/volume (D=M/V) (DSB). We can visualize the relationship between these three variables in an intuitive way using a model of dots (representing amount of material or mass) and boxes (representing volume) (IR). The extent to which dots are packed into boxes represents density (IR). Thought about in this way the concept of matter refers to many things in the world including clearly solids and liquids, but also powders that seem negligibly light or gases that we may not be able to see or feel. It is this whole collection of various kinds of knowledge elements that constitutes the scientific concept of matter at this level. (Of course, this can get more sophisticated at more advanced levels.)

The Good News and the Bad News for Educators

What does this characterization of scientific concepts mean for educators? In this section, I discuss this question starting with the good news and then turning to the bad news. The good news is that the multiple components that make up concepts can be seen as resources readily available to the learner. The bad news is that it becomes clear that learning a concept involves the challenging task of coordinating multiple knowledge elements. So let's start with the good news.

The components of concepts as resources

As indicated above, we can list the following types of knowledge elements that constitute a scientific concept: domain specific beliefs, metacognitive and epistemological beliefs, and iconic representations like images, image-schemata and mental models. A useful way to organize a discussion of different types of knowledge is in terms of format, how that knowledge is represented. In cognitive science an important distinction is often made between propositional and non-propositional representations. Propositional representations are language-like with a truth value – i.e. can be judged to be true or false statements about some state of affairs in the world –. Statements in natural language or mathematically expressed relationships between numerical quantities are examples.

Non-propositional representations bear a relationship of similarity to what they represent. An nonpropositional representation can be more or less similar to what it represents but cannot be judged to be true or false. Mental imagery is the clearest example of non-propositional representations. Another example is image schemas, which are abstractions from sensorimotor experiences. Mental models, analogical representations of objects and events, which support dynamic simulation and reasoning by coordinating imagery and image schemas are a third. In the rest of this section, I illustrate each of these knowledge types using examples from science, and discuss how such elements can often be seen as readily available to learners. I then turn to two types of knowledge elements – symbolic forms and conceptual metaphors - that can be seen to be combinations of both propositional and non-propositional representations.

Examples of propositional representations in science are “Temperature is proportional to kinetic energy,” “F=ma” and “D=m/V.” Each of these constitutes a claim about a state of affairs in the world and can be shown to be true or false. These can be referred to as domain *specific* beliefs as they are statements about specific domains – i.e. thermodynamics, mechanics and particulate theory of mater, respectively. Other propositional representations can be *meta*cognitive, that is, *about* knowledge more generally. For example, we may hold the belief “Measuring instruments are more trustworthy than the senses” or “Diagrams or models capture only some aspects of what they represent”.

Whether domain specific or metacognitive, we would associate the examples I just listed with accurate scientific knowledge, so in what sense can these be seen as resources “readily” available to the learner? If these are beliefs that constitute parts of scientific concepts, how can recognizing this be seen as part of the “good” news for educators? The answer to both questions is to see these beliefs written in quotes above as (simply) what they are, *representations*. All learners can hear these statements uttered by a teacher or read them in a textbook and remember them. Indeed rote memorization of curricular content is never seen (by teachers or learners) as a challenging aspect of learning concepts. The problem is identified more with meaningful understanding of these remembered representations. But in what sense are these useful “resources”? A recent account of concept development has recognized that just such shallowly understood propositional representations play the important role of creating symbolic placeholders for the relationships between concepts that need to be understood (Carey, 2009). Simply remembering that "density = mass/volume" provides a useful starting point for developing a conceptual understanding of the concept of density and a scientific understanding of matter. That understanding will come from grounding the interpretation of propositional representations in the intuitive understanding derived from non-propositional representations, which I turn to next.

The first kind of non-propositional representation I will consider is imagery. John Clement and his collaborators (e.g. Clement, 2008; Stephens & Clement, 2006) have shown that school aged learners will use imagery to make sense of scientific concepts presented to them just as scientists do when presented with novel situations that require them to make creative leaps in their understanding. Clement and his colleagues have been devising methods to uncover instances of the use of imagery by students in classroom settings. Central to these methods is the identification and analysis of the use of gesture as a basis for inferring the use of imagery. This is illustrated in the annotations of a student's use of gestures while responding to a teacher's question about gravity at different locations on the Earth's surface. The student is making reference to a diagram drawn on the board of two stick figures on either side of the Earth represented as a circle:

> T: Compared to the US, gravity in Australia is: a little less, equal, a little but more?
> S: Well I just think that gravity has nothing to do with rotation, but maybe with [**quick rotating movement with right forefinger]** rotation like [**points to chalkboard**] that guy is trying

> to get [**emphatic movement with his right hand and arm, beginning on the right side of his body and sweeping leftward in front of him**] thrown off the Earth. So he's getting [**repeats sweeping movement**] pulled at the same rate but he's also getting [**reverses previous movement, pulling his right hand and arm back to the right**] pushed away. (Stephens & Clement, 2006)

According to Stephens and Clement (2006), this student's response and the gestures accompanying it reveal the use of imagery. That is, the student is creating a mental image which is simulating the two different types of rotation that the Earth undergoes. This imagistic simulation is enabling him to reason through to a possible answer to the question posed by the teacher (not included above). In this context, "imagery" is understood as mental reenactment of objects and events in the 'mind's eye˒. The research of Clement and colleagues has shown that engaging in imagistic simulation is something that learners can and *do* do even in the absence of explicit instruction to do so.

The next kind of non-propositional representation to consider is *image schemas*. Image schemas are understood as abstractions from sensorimotor experiences. From infancy we begin to interact with the world in various was, pushing, pulling, putting things in and taking them out of containers, we lose and regain our balance while walking and sitting and so on. All of these interactions involve sensory experiences of perceiving the objects we interact with and motor experiences in which we are aware of our own actions and the bodily sensations that accompany them. When similar sensorimotor experiences of this kind recur we abstract the core, generalizable elements of these experiences. For example, from many different experiences pushing all sorts of different things to move them from one place to another, we abstract the core elements of *sense of agency associated with exerting a force on an object which results in some motion*. These abstracted core elements form a structure (or “gestalt”). Although it derives from sensorimotor experiences, once abstracted it becomes a *mental* structure that can be invoked in the absence of the sensorimotor experiences themselves that gave rise to the structure in the first place. Thus, image schemas can support *conceptualizing* including categorizing things and making inferences about them (Mandler, 2004).

In science education research, diSessa (1993) made the claim that our intuitive understanding of objects and their interactions is grounded in many image schemas, which he called phenomenological primitives (or p-prims). The image schema glossed above corresponds to what diSessa called the *force-as-mover* p-prim. He has described many others such as *balance* and *overcoming*. He hypothesizes that we all develop hundreds, if not thousands, of such structures throughout our lives and they form the intuitive basis of our sense making about the physical world. He also goes on to argue that these structures continue to play a very productive role in *scientific* understanding and sense making.

David Brown and John Clement (Brown & Clement, 1989; Clement, 1993) provide a particularly dramatic illustration of this productive role in their method of bridging analogies. They used this method to help students understand the idea that any surface exerts an upward normal force equal to the downward force of gravity exerted on an object resting on the surface. They first note that the learning challenge is of accepting the unintuitive idea that an apparently inert surface (of a table, for example) can be seen as exerting a force. In order, to help students make sense of this idea they search for what they call an anchoring intuition: a situation where an upward force on an object being pulled down by gravity *is* intuitive – e.g. a book placed on a spring. The method of bridging analogy recognizes that learners may not readily accept the similarity of the anchor and the target situation, so they come up with a bridge – a situation that resembles both the anchor and the target (e.g. a thin plank of wood that is "springy" but still made of wood like a table). The bridging analogy technique works, according to Brown and Clement, because it encourages the learner to draw on an intuitive knowledge structure (= image schema, p-prim) that is intuitively and readily invoked in some situations but with the instructional support of the bridging analogy can be shown to be appropriate in a target situation.

A final type of non-propositional knowledge element available to learners is not so much a new type as much as a combination of two others. When images and image schemas get invoked together the result is a mental reenactment of objects and events which is interpreted in terms of image schemas. The result is a mental model which allows someone to reason about the dynamic and causal features of a situation generating predictions of what will happen or explanations of what has been observed. We have already seen an example but it wasn't discussed in relation to the idea of a mental model. If we return to the excerpt of the student reasoning about gravity at different locations on the Earth we will notice that he was not just enacting the movement of the Earth but was invoking causal relations (he talked about the guy being "thrown", "pushed" and "pulled"). That is, he was *interpreting* the image he invoked with image schemas of force interactions between objects to reason through the implications of being at different locations of the Earth for the force of gravity on a person. What he did was construct a mental model of a situation which enabled him to enact this situation in his mind and consider the implications for the forces involved. Mental models have been identified in characterizations of intuitive, prescientific understanding in many domains (Gentner & Stevens, 1983) and have been shown to play an important role in scientific cognition as well (Nersessian, 2008).

Before concluding this section, I will mention two more types of knowledge elements that constitute scientific concepts but which need to be characterized in terms of both propositional and non-propositional components; these are conceptual metaphors (Lakoff & Johnson, 1980) and symbolic forms (Sherin, 2001).

Over three decades ago now, the linguist George Lakoff and the philosopher Mark Johnson wrote a book entitled *Metaphors We Live By* (1980) that generated a great deal of interest in linguistics and in cognitive science, more generally. In that book, they pointed out that everyday language is full of implicit metaphors that had not been recognized. They also argued that these metaphors are so pervasive and systematic, suggesting that they reflect an underlying conceptual phenomenon that many abstract concepts are understand in terms of metaphor. They illustrated this point by showing very many patterns in everyday language use. For example, in reference to relationships we would say ‘We're at a crossroads,’ ‘We've had a parting of the ways,’ ‘Look how far we have come’ and ‘It’s been a bumpy road.’ Lakoff and Johnson pointed out that all of these statements (and many more) reflect an underlying conceptual mapping that they called Love Is A Journey. This kind of mapping between the domain of love/

relationships and traveling in a journey they called a conceptual metaphor. They discuss many more examples in their book (e.g. Time Is A Resource; Argument Is War) and the implications of the phenomenon of conceptual metaphor for how we should understand how our conceptual systems work. The central idea was that our understanding of abstract concepts that cannot derive directly from experience is based on mapping of knowledge from more familiar conceptual domains. Since the book appeared in 1980, there has been a great deal of work on conceptual metaphor by Lakoff and Johnson themselves and others. More recently, they have shown that many of the conceptual domains that are mapped to abstract concepts are themselves structured in terms of image schemas (described above) such as *containers*, *possessions*, *movement of possessions*, *paths*, *forced movement along a path* and others (Lakoff and Johnson, 1999).

Based on the analysis of the metaphorical use of the term "energy" in *Feynman's Lectures on Physics*, I showed how pervasive the phenomenon of conceptual metaphor is in the language of science as well and that it is likely that this reflects conceptual mapping between image schemas and abstract concepts in science as well (Amin, 2009). For example, we see energy is systematically construed as a *substance* (e.g. 'How much energy does it *have*?'), change of energy state construed as *movement of a substance* (e.g. 'It *lost* energy to the surroundings.'), and forms of energy are construed as *container* (e.g. 'The energy was *stored in* the compression of the spring.') The phenomenon of conceptual metaphor as implicit in the language of science is now being studied extensively (see a special issue on the topic, Amin, Jeppsson & Haglund, 2015). Many issues of relevance to science learning and teaching have been explored, including the metaphors implicit in the language of science to which students are exposed, the metaphors used by students themselves to construe an abstract scientific concept, the incorrect interpretations that learners will sometimes give to the metaphors they are exposed to, the role that metaphors play in problem solving, and how analogies and visual representations can be selected and designed to help learners correctly appropriate the conceptual metaphors in a domain they are learning. What's particularly important to highlight for the purposes of this paper is that when students get exposed to challenging scientific language when they learn science, that language has verbal clues (in the form of spatial prepositions, concrete action verbs and others) to image schemas that will be useful to them as they try to make sense of difficult abstract concepts. Non-propositional image schemas are triggered by elements of (propositional) linguistic expressions that implicitly encode a metaphorical expression.

An analogous phenomenon has been identified in mathematical equations but is less transparent to the learner. Bruce Sherin (2001) has analyzed problem solving sessions of advanced physics students. Through careful analysis of the transcripts and video recordings of these sessions, Sherin was able to identify an important knowledge resource that enables successful problem solving, a resource he calls symbolic forms. As Sherin explains, symbolic forms are associations of symbol patterns of equations and conceptual schemata. For example, consider the pattern of two terms on either side of an equal sign (□ = □), two terms separated by a minus sign (□ - □) or a term divided by an increasingly larger term (□ / □). Sherin calls the generic pattern in each of these examples a symbol template. He found that advanced physics students would parse physics equations using such templates and would associate them with some kind of conceptual schema that would enable them to make sense of the equation. In the three cases just discussed, the conceptual schemata would be *balancing*, *opposing influences*, and *dying away*, respectively. Interpreting equations in this way enabled the problem solvers in Sherin's study to connect the quantitative relationships expressed in an equation with the physical situations they were thinking about; that is, the symbolic forms helped problem solver coordinate qualitative and quantitative understanding of the problem situation.

Identifying the use of symbolic forms in the thinking of advanced problem solvers is to identify symbolic forms as contributors to expertise. However, what is important to point out in the context of this paper is that the conceptual schemata that make up part of symbolic forms are essentially image schemas which are readily available to a learner. As in the bridging analogies strategy, the instructional challenge is to find ways of encouraging learners to trigger the right image schema at the right time. While I know of no study that explores how the use of symbolic forms to interpret physics equations can be taught, it is clear that a key component of this knowledge resource is available to the learner and is waiting for the teacher (or the learner) to find a way to invoke it appropriately.

The challenge of coordinating knowledge resources

The previous section surveyed the various knowledge elements that are the components of scientific concepts and showed that these elements (or at least aspects of them) can often be seen as readily available to learners and can serve as the basis upon which learners can build their understanding of difficult concepts. That was the good news for educators about the nature of scientific concepts. The *bad* news for educators is the other side of the coin of breaking concepts down into a collection of multiple parts. The result of breaking concepts down in this way shows that they are complex knowledge systems (see also Brown & Hammer, 2008; diSessa, 2002 for different views of this complexity) and that to understand a concept is to coordinate a large collection of knowledge elements of different types and formats. It is here that we must identify the key challenge of instruction.

Some progress has been made in dealing with this complexity in the science education literature but in select domains and much work still needs to be done. Smith and Wiser (2013) give a detailed account of the elements that need coordinating for children to develop a (more) scientific understanding of the concept of matter, to return to the example elaborated earlier in the paper. First, the instructional approach taken builds on and transforms the following ideas available to learners early on, many of which are in the form of non-propositional representations:

- A notion of object in which shape and size are understood as invariant and important for actions; understood to be countable; but *not* yet construed as materials.
- An understanding of *non*-solids that do not maintain shape; are not quantifiable; may lack permanence; but *are* construed as materials.
- Subjective understanding of weight as heft, resulting in the view that very small things weigh nothing; this notion of weight is conflated with density.
- In this early understanding, bigness conflates length,

area and volume; qualitative comparisons are possible but not quantified.
- The metacognitive belief that what you sense (see, feel) is what is there; thus, matter/stuff is that which is seen, felt, touched (so gases are not included).

Some informal learning processes and thoughtful instruction can build on these existing understandings, make use of propositional placeholders and encourage the triggering of useful non-propositional knowledge elements. The following informal processes and formal instructional interventions have been found to contribute to developing a more scientific concept of matter.

- Natural, everyday exposure to linguistic constructions (e.g. [material name] [object name] or X is made of Y) which function as placeholders guide understanding of material kind (e.g. plastic, wood).
- Assisted construction of a macroscopic compositional model needed for amount of material.
- Experiences measuring weight with scales and being taught a concept of measure can guide construal of weight in terms of amount of material (invariant across reshaping and resizing) which then leads to a more objective concept of weight; here representations of quantity serve as placeholders.
- Experiences measuring length, area, volume help differentiate these from each other after being conflated in “bigness;” again, representations of quantity serve as placeholders.
- Inquiry activities exploring volume vs. weight relationships and identifying families of materials with common ratio support the understanding of density as distinct from weight; and again, representations of quantity serve as placeholders.

- Repeated division and weighing activities followed by discussion (supported by imagery) of what happens if we imagine keeping on dividing leads to an imagistic representation of invisible particles.
- Modeling activities (not didactic instruction or unguided inquiry) and explicit instruction about modeling help develop explicit epistemological beliefs about models.

Together, all this leads to a macroscopic particulate model of matter, which is a useful stepping stone to a more scientific understanding. This work by Smith and Wiser (2013) on developing an understanding of matter is conducted within the broad perspective of learning progressions (see Wiser, Smith & Doubler, 2012). From this perspective core domains of conceptual knowledge are identified as central to developing a basic scientific understanding. It is recognized that learning must begin from the conceptual resources children bring to formal instructional settings. It is also recognized that designing instruction has to focus on coordinating multiple knowledge elements (both domain specific and metacognitive) and will be in propositional and non-propositional formats.

A number of other approaches to curricular and instructional design that embrace the challenge of coordinating multiple knowledge elements include: Knowledge Integration, in which extended middle school units are organized around models of intermediate abstraction (Linn, 2008); Learning Goals Design, in which concept learning is developed in the context of inquiry with emphasis on "knowledge-building" where standards, curricular units and assessments are aligned (IQWST middle school project) (Krajcik, McNeill, & Reiser, 2008); and the integrated science and mathematics modeling curricula in elementary years (Lehrer & Schauble, 2000).

Conclusions

In sum, the fields of cognitive science and science education have provided us with a view of concepts as complex knowledge systems. The components that make up these systems are largely available to the learner. This is good news for educators who seek to guide learners to develop meaningful conceptual understanding. The challenge, however, is to guide learners to invoke the resources they have available at the right time and in the right context and to coordinate these multiple resources in ways that resemble what scientists themselves do. There has been some progress in the science education literature to design instructional interventions and curricular sequences that can achieve the needed coordination. But this has been limited to relatively few domains. Moreover, some elements such as conceptual metaphors and symbolic forms are yet to be addressed in these larger scale investigations into instructional and curricular interventions (but see the contributions in Amin et al., 2015 for initial attempts to design instruction in light of the phenomenon of conceptual metaphor). Future work will need to both broaden its scope to address a wider range of domains and deepen its focus to address more knowledge elements within a conceptual domain.

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