Student Conceptions and Conceptual Change:

Three Overlapping Phases of Research[1]

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From the 1970's onwards, researchers have tried to understand the content and nature of student conceptions, how these conceptions can both hinder and contribute to learning, and how student conceptions change to resemble those of scientists. Progress in understanding student conceptions and the process of change has led to suggestions for how to design more effective instruction. The literature on student conceptions and their change is vast, as evidenced by a periodically updated bibliography containing thousands of publications (Duit, 2009). No single review can do justice to it all.

Over the years, others have reviewed many aspects of this literature. We have approached ours in an effort to complement previous contributions. Driver and Easley (1978) drew attention to the specific content of student conceptions as researchers on science learning increasingly rejected the Piagetian stage view of concept development. Smith, diSessa & Roschelle (1993) cautioned researchers against overlooking the positive contributions of students' conceptions to the learning process. Sinatra and Pintrich (2003) reviewed the connections between metacognition, epistemology, intentional learning and conceptual change. diSessa (2006) highlighted the disagreements over the coherence versus fragmentation of student conceptions. Scott, Asoko and Leach (2007) contrasted cognitive and social perspectives on science concept learning. Vosniadou (2008) surveyed the broad scope of the research, which spans student learning, the philosophy and history of science, and research on topics beyond science, including mathematics and history. Mason (2007) discussed attempts to bridge cognitive and social/situated perspectives on conceptual change.

In our review, we take a broad, yet loosely historical perspective. While we acknowledge diverse perspectives, we believe that a broad historical view of the field over the last three to four decades reveals some steady progress, which we characterize in terms of three distinguishable (but sometimes overlapping) phases. The first phase (the 1970s and 1980s) was united in revealing the importance of characterizing student conceptions in specific domains, thereby rejecting a domain general view of concept development. A second phase (1990s and early 2000s) focused on understanding the process of change, recognizing that a range of diverse knowledge elements were involved. The third phase, currently underway, sees researchers increasingly adopting systemic perspectives – characterizing concepts and conceptual change and designing instruction taking into consideration the interaction of various knowledge elements at multiple levels of analysis.

In addition to outlining this three-phase picture of the history, we have a number of parallel objectives. Although we focus on research on conceptual change within science education, we also clarify contributions made by foundational research in developmental psychology and cognitive science. Moreover, while we review research conducted from a variety of perspectives, our engagement with the literature is framed within a cognitive perspective. We assume that understanding student conceptions and conceptual change requires us to posit *internal* mental representations and processes of various kinds, which interact with external representations and social processes. With regard to "bridging the cognitive and sociocultural approaches" to conceptual change, Mason (2007) asks: "Is it feasible?" We assume such bridging is feasible, and that this is apparent in the research synthesis that we offer here.

Phase One -- Emergence of Domain-specificity and the Importance of Qualitative Reasoning in Science

One can trace the "modern" era of conceptual change as an approach to studying science learning to several sources: widespread attention to students' misconceptions; a broad rejection of empiricism; and psychologists' disenchantment with Piaget's theory. New perspectives in psychology and philosophy of science provided science educators with theoretical frameworks for interpreting students' ideas, understanding learning processes, and designing teaching interventions, although Piaget's influence (both positive and negative) remained strong in science education at large.

On the positive side, Piaget's constructivist and "child-centered" approach prefigured the view that students bring their own ideas to science classrooms, and should be constructing their own knowledge. Assimilation and accommodation as engines of conceptual development, and the role of measurement and mental schemas (e.g., atomistic schemas) in constructing quantities (e.g., weight and volume) (Piaget & Inhelder, 1942) are part of many contemporary views. But his account of development as a succession of stages with different logico-mathematical structures implies a "logical deficit" view of young students that had a detrimental effect on science education. He proposed that *preoperational* children's (preschoolers and kindergartners) understanding of the physical world is perceptually bound, non-causal, and based on pre-concepts; that *concrete operational* children (6-12 year olds) can only reason about concrete situations; and that it is not until the *formal operational* stage (adolescence) that children can reason in a hypothetico-deductive manner, and are capable of model-based reasoning and theory building and revision - i.e. of scientific thinking (Inhelder, Piaget, Parsons, & Milgram, 1958). His emphasis on hypothetico-deductive reasoning as the hallmark of science misses important aspects of scientific practice such as qualitative reasoning and developing descriptive or even explanatory models (Acher, Arca & Sanmarti, 2007; Lehrer & Schauble, 2000).

Piaget's view of concepts as sets of necessary and sufficient features, conceptual structure as mainly hierarchical, and class inclusion as essential to achieving concepts is similarly restrictive (i.e. a "classical" view of concepts). Although he related some concepts to each other (e.g., amount to weight and volume), he was essentially focusing on concepts in isolation of each other. Making conservation the cornerstone of achieving concepts of quantities and contingent on logical operations (reversibility, coordination of dimensions) distracts from the complex construction of the *content* of concepts themselves, the more *qualitative* aspects of their meaning, and how they relate to others (e.g., the concept amount of material develops in relation to the concept of material itself).

This overly logico-mathematical view of science, concepts, and learning, contributed to the sharp divide that still exists, between elementary school standards and curricula, on the one hand, and middle and high school ones, on the other. Perhaps overplaying the limitations of concrete operational thinking, most elementary school science education has been based on a-theoretical observations and hands-on experiments (Metz, 1995). Given the centrality of self-regulation of mental structures in Piaget's theory, their focus is not which concepts are presented in what order, or on the relationship among concepts themselves, but on the relationship between concepts and logical structures. Moreover, it is easy to (mistakenly) attribute logical (and therefore conceptual) changes to maturation, because Piagetian accounts of how knowledge acquisition can lead to the construction of more powerful logico-mathematical structures are somewhat obscure. In addition, the Piagetian view that elementary school children are inescapably “naïve realists” while high-school students are “inescapably” capable of hypothetical reasoning, is probably an important reason that the relation between conceptual content and epistemology was not initially explored.

From domain general logical structures to domain specific content structures in cognitive science

Starting in the 1970s, several strands of research in psychology challenged Piaget’s domain general account of development with its focus on logical structures. While endorsing constructivism, sharing his concern for the structure of knowledge, and acknowledging that children often have very different ways to interpret the world, developmental psychologists started to question the psychological reality of broad logical structures at different stages of development. Evidence was mounting that preschoolers, although more perceptually bound than older children, can also show evidence of reasoning abilities characteristic of Piaget’s concrete operational stage (e.g., distinguishing appearance from reality, expecting cause-effect relations to be mediated by unseen mechanisms, and reasoning in terms of conservation and class inclusion (see Gelman & Baillargeon, 1983). On the other hand, hallmarks of hypothetico-deductive reasoning (e.g. distinguishing theory from evidence, understanding the nature of scientific models) were found to pose major difficulties to most adults and adolescents (D. Kuhn, 1989; Grosslight, Unger, Jay, & Smith, 1991). For children of all ages, reasoning abilities were more advanced in familiar contexts (Donaldson, 1978), suggesting that reasoning involved representations of content as well as logical abilities. Moreover, Piaget’s theory could not account for “decalages.” If concepts such number, amount, and weight depend on the acquisition of the same logical structures and operations, why are they not conserved at the same time?

A different line of research, on the “novice-expert shift,” strengthened the view that reasoning and some aspects of knowledge structure depend on amount of knowledge in a specific domain. Some children develop extensive knowledge networks in a domain (e.g., dinosaurs), which has far-reaching effects on inference, memory, and categorization performances (Chi, Hutchinson, & Robin, 1989).

Thus there was a shift to a *continuity* view of conceptual change: children are capable of abstract and rational reasoning from a very young age, but younger children are less likely to display advanced reasoning skills because they *know a lot less* (Carey, 1985a). Making conceptual change *content-based* also makes it *domain-specific*—e.g., the developments of concepts about the physical and mental world are different and independent—and takes care of Piaget's decalages. The continuity view, however, encountered difficulty accounting parsimoniously for the radical qualitative differences in how younger and older children explain some phenomena (e.g., trait inheritance, matter transformations). Help came from T. Kuhn's work *(*1962; 1977) in the philosophy of science, which provided a framework for privileging content in conceptual change, as opposed to logical structure. He viewed theories as "substantive" (rather than logical) systems, and proposed that scientific concepts take their meaning from the theories of which they are part. Thus the same term (e.g., force) takes radically different meanings in different theories.

Carey (1985b) used a Kuhnian approach to explain the differences between older and younger children's reasoning as radical changes in the contents and relationships of concepts. She contrasted *strong* and *weak restructuring*. In weak restructuring concepts are enriched, superordinates and other relationships among concepts are acquired, but their core meaning stays the same. In strong restructuring, concepts change; they may differentiate, coalesce; appear, or disappear, and relations among them are fundamentally altered. Explanatory mechanisms and ontology (one's understanding of what kinds of entities there are in the world) also change. For example, Carey proposed that young children think of animals only as "behaving beings" whereas older children think of them as biological entities as well. This change includes a change in domain (young children's behavioral explanations do not apply to plants), in explanations for behaviors such as eating, and in many concepts (e.g., death) and conceptual relations.

The *theory-theory* (e.g., Gopnik & Wellman, 1994) was a strong version of Carey's proposal. It highlighted the parallel between children and scientists at the level of theory (vs. conceptual) change, and drew attention to young children’s use of abstract entities in their explanations (e.g., “A is heavier than B because the *stuff inside is more packed*.”) Cognitive scientists were also foregrounding the content, explanatory role, and domain specificity of adult concepts, as they were abandoning the classical view for *explanation-based views* in which concepts are “large chunks” of knowledge that explain aspects of the world (Murphy & Medin, 1982).

In sum, cognitive psychologists were developing a new framework for understanding concepts and conceptual change. It was content-based and domain specific; assumed that knowledge was organized in deeply similar ways to scientific theories; and foregrounded explanatory causal mechanisms and multiple relations among concepts. It was continuous in that it granted young children the same *kind* of concepts and conceptual organization as adults, and that conceptual *content* could be traced across development. It could explain how young children’s thinking could be at the same time so similar and so different from older children’s, adults’, and scientists’ by proposing that concepts can radically change while the format of representation stays the same.

From domain-general to domain-specific science learning

The shift away from a domain-general account of conceptual change found its counterpart in science education. The dominant approach to science education in previous decades had emphasized scientific inquiry and hands-on activities, as sources of data from which students were expected to induce general principles, a pedagogy reinforced by Piaget’s view of the child as actively constructing knowledge. Underlying this pedagogy (although at odds with Piaget’s constructivism) was an *empiricist epistemology*: all knowledge derives from sensory experience and is accretive; if students are trained in the scientific method correctly, they will induce principles that get closer and closer to those of science.

In the 70s, educators were becoming more and more aware that students of all ages evince profound difficulties with all core scientific ideas (e.g., evolution), principles (e.g., Newton’s laws) and models (e.g., models of the earth) and hold beliefs incompatible with those of scientists. The ubiquity and resiliency of student misconceptions testified to the limitations of the "discovery" movement. Classroom observations showed that misconceptions do not result from faulty observations or illogical reasoning. Rather, students interpret observations and assess new ideas in light of their pre-instruction conceptions. Widespread consensus developed about a *conceptual change* approach to science teaching, seeking to foster *understanding* and *adoption* of scientific ideas as new systems of interpretation. Kuhn's argument that observations are theory-laden and that concepts take their meanings from each other within knowledge systems, applied to science students as well (Strike and Posner, 1985). In sharp contrast to this prevalent approach, which we will call the "coherence view", diSessa (1993a) promoted a "knowledge-in-pieces" view—students interpret events in terms of isolated phenomenological primitives ("p-prims"); the goal of science education should be to reorganize those p-prims, subsuming them under scientific concepts and principles.

We refer the reader to several cogent reviews of conceptual change in science education during this period (e.g., Driver & Easley, 1978; Scott, Asoko, & Driver, 1992; Vosniadou & Brewer, 1987). We focus here on two debates: a) the extent to which students' preconceptions were coherent; and b) the extent to which conceptual change involves transformation vs. replacement. While agreeing that instruction should take students' initial ideas into account and scaffold students' understanding of scientific ideas, different theorists characterized the structure of students' ideas in different ways, and proposed different instructional models.

The parallel between some students' misconceptions and early scientific ideas (e.g., Aristotelian understanding of motion) combined with the popularity of the theory-theory in psychology led to the "knowledge-as-theory" view in science education (e.g., McCloskey, 1983). McCloskey made the strong claim that "people develop on the basis of their everyday experiences remarkably well articulated naïve theories of motion,…best described as different forms of the same basic theory. [The theory] is strikingly inconsistent with the fundamental principles of classical physics. [It is] similar to [the medieval impetus theory]" (McCloskey, 1983, p. 299). Strike and Posner (1985) softened this position by acknowledging that student theories are not explicit. Adopting a Kuhnian perspective, they proposed a four-step normative model of science learning based on conceptual change as theory change: 1) students become dissatisfied with their current conceptions; 2) new conceptions are “minimally” understood (i.e., students grasp the new conception sufficiently to want to explore it); 3) the new conception is made plausible (i.e., it explains what the old conception explained, and fits with other knowledge and experience); and 4) the new conception is seen as fruitful (e.g., it has greater explanatory power or applies to more phenomena). Moreover, they proposed that conceptual change took place within *conceptual ecologies*—including anomalies, analogies, metaphors, epistemological beliefs, metaphysical beliefs, and knowledge of other areas of enquiry. While not developed empirically, this idea prefigured systemic perspectives we discuss later in this chapter.

Strike and Posner’s model may not have been “Kuhnian enough,” however, in the following sense. Missing is one of Kuhn’s themes— theories are resistant to change because they consist of networks of interrelated concepts that give meaning to each other. Their purely epistemological and rationalist perspective only addresses why one would choose one theory over another, not how one comes or fails to understand them, and therefore ignores a paradox: in their model, students appraise their existing theory vis-a-vis candidates for replacement, something they can only do in terms of concepts they already possess. At the same time, new concepts take their meaning from the new theory. How can a new concept be meaningful before the whole theory is understood, and how can the whole theory be understood if not one concept at a time? Moreover evaluating the relative merit of two theories requires epistemological sophistication beyond most students, many of whom have difficulty distinguishing theory from evidence, and understanding the nature and function of scientific models.

Carey (1985b), Vosniadou and Brewer (1987), and their collaborators, also viewed conceptual learning in science as theory change but their levels of analysis and the epistemological issues they took into account were different from Posner and Strike’s. They characterized the content and structure of children’s knowledge before instruction in several domains (biology, the day/night cycle, the earth, matter, heat/temperature), providing evidence for its theory-like nature, and identifying the conceptual changes needed to transform that knowledge inherent to theory change. Theory-theorists were constructivists, in the sense that they saw children’s theories as knowledge structures that were transformed by experience and instruction, not something to replace.

Other theorists (e.g., Driver, Guesne & Tiberghien,1985; Nussbaum & Novick, 1982; Osborne and Freyberg, 1985) also viewed children's ideas as coherent but not embedded in theories. Individual interviews, classroom observations, and teaching studies documented children's ideas in many scientific areas, including matter, force, motion, energy, and photosynthesis. Driver (1983) referred to students' ideas as "alternative frameworks" to emphasize the coherence, stability, and rationality of students' knowledge, and its resistance to change.

The instructional implications of students' alternative conceptions were clear: teachers should choose classroom activities and lessons that bring out students' own ideas and help students reflect on them. Educators disagreed, however, on whether students' ideas should be replaced by scientific ones (as advocated by Strike and Posner), or transformed into them. According to the replacement view, teachers should create explicit conflicts between students' and scientific frameworks, make scientific ideas understandable, and promote their adoption (e.g., Driver, 1983). In contrast, the transformation view promoted capitalizing on students' ideas rather than confronting them, and restructuring knowledge systems by progressively integrating new pieces of information into them (Osborne & Freyberg, 1985).

Whereas the coherence view treats students' ideas as alternatives to scientific ones (although not necessarily as theories themselves), diSessa sees a profound ontological difference between students' ideas ("p-prims") and scientific theories. *Towards an Epistemology of Physics* (diSessa, 1993) outlines a theory of knowledge development, which is, in many ways, more specific and richer than the coherence views mentioned in the previous section. It is also radically different from them in some ways but, we will argue, less so than stated in the paper, and reflected in subsequent articles.

What diSessa calls "naïve physics" consists of a large number of phenomenological primitives or "p-prims." P-prims are small knowledge units, intermediate between percepts and concepts. For example, the "Ohm P-prim" (which has the schematic form "an *agent* is the locus of an impetus that acts against a *resistance* to produce some sort of *result*") implies, "more resistance, less result; more effect, more result." P-prims are "minimally" abstracted from sensory-motor experiences, in that they are explanatorily shallow, and have limited conscious access; and their use is extremely context-dependent, although they can be applied to broad ranges of phenomena. Some p-prims are domain-specific, some are not.

To students, p-prims have the same "irreducibility" and explanatory force as theoretical principles to physicists, but of course are profoundly different from them. P-prims are weakly organized; they rarely entail one another. There is no rational necessity for applying p-prims to particular contexts. In other words, naïve physics is loosely organized, implicit, and "unreliable" knowledge. However, diSessa sees strong continuity from novice to expert. Students' ideas are not misconceptions, because they are not explicit beliefs, but the product of occasional mismatches between p-prims and contexts. Teaching physics should aim at reorganizing p-prims to subsume them under theoretical principles, which form a new level of representation. As they do, p-prims lose their "irreducibility" to become distributed encodings of the theory. diSessa speculated that equations and verbal statements expressing the theory's laws and principles help organize the p-prims. Each p-prim plays a role in "knowing" a principle; together, they "unpack" the meaning of scientific laws and principles according to contexts.

diSessa contrasted his theory to McCloskey's, which is not prototypical of the "knowledge-in-theory" view, let alone of the coherence approach as a whole. On epistemological grounds, he questioned attributing to students beliefs that are theoretical, universally applicable, and "false." On empirical grounds, he argued that McCloskey's evidence could be fruitfully re-interpreted in terms of p-prims. Unfortunately, this rebuttal downplayed possible commonalities of the knowledge-in-pieces and coherence views other than McCloskey's, and shortchanged in-depth comparisons of various researchers' units of analysis, views of students' ontologies, epistemologies, and conceptual coherence, and of the process of conceptual change itself.

Phase One was the beginning of a paradigm shift, an exploratory phase; research focused mainly on describing the phenomena (students' ideas) that were instrumental in rejecting the old paradigm, and finding appropriate frameworks to interpret them, and help students develop scientific ideas. Those new frameworks embodied a domain-specific, content-based view of science learning, which still holds today. Ausubel (1968) and Novak (1977) had called attention to the importance of *students' preconceptions* and to the need to answer a number of "big questions:" How does students' thinking change over time in reference to core scientific concepts? In what ways do students' existing ideas influence the assimilation of new information? Under what circumstances do "misconceptions" contribute positively to conceptual growth (Ault, Novak, & Gowin, 1988)? As they were beginning to answer those questions, education researchers were discovering that conceptual change was more complex and harder to foster than expected initially, and that more sophisticated instructional models were needed.

Phase Two – Recognizing the Multiple Components of Conceptual Change

Phase Two research began to examine the process of conceptual change more closely and, in so doing, identified a variety of cognitive components operating at different levels and varying in their scope of applicability. Of particular interest has been the relation between conceptual change and: (a) changes in broad *ontological* categories; (b) increasing sophistication in *epistemological* beliefs; (c) the use of *models* and modeling; and (d) the dynamics of communication and *social interaction*. While there are other influences on conceptual change, we think these four components are inherent to conceptual change in ways other influences are not. We review research in each of these four strands pointing out influences from fields outside science education as well.

Ontology

As researchers began to explore the processes of change, many noted that learning science concepts was especially difficult when it involved major ontological shifts – for example, from thinking of: the Earth as a physical to astronomical object (Vosniadou, 1994); heat as hotness to exchanged energy (Wiser & Amin, 2001); or force as a property or material substance to a constraint-based interaction (Chi, 1992). Ontology became an object of study in its own right in an effort to understand sources of coherence in naïve views and resistance to change. However, researchers *varied* in how they characterized naïve and scientific ontologies, saw the relation between the two, and designed instruction to develop scientific ontologies. For Chi (1992), naïve and scientific ontological categories were defined in more domain general terms and were thought to be amenable to direct instruction via replacement strategies. For others, the development of ontological categories was seen as a gradual transformational process, building on precursor concepts, and tied to multiple domain specific processes of theory change (Nersessian, 1989; Vosniadou, 1994; Wiser & Amin, 2001). Vosniadou (1994) also proposed that ontological and epistemological commitments defined a broad framework theory that constrained how students formed more specific models and theories.

Chi's influential domain general approach rests on the assumption that concepts belong to categories, and inherit the properties of the category to which they are assigned. Building on the work of Keil (1979), she viewed ontologies as nested *categories* within abstract hierarchical trees (e.g., *material entities, processes,* and *mental states*), organizing conceptual knowledge and the predicates that can span terms that designate concepts in the hierarchy. She and her colleagues were especially interested in students' understandings of distinctions within the ontological category of *processes*, because many science concepts are processes, and modern science has changed the fundamental way we think about them. For example, Chi and Slotta (1993) contrasted the subcategory of *events* (time-bound, causal processes that are part of our common sense ontology) with *constraint-based interactions* (an ontological subcategory they proposed was important in science but missing in everyday ontology). They argued that students have difficulty with many physics concepts, such as force, heat, diffusion, and natural selection because they assign them to the wrong ontological category (e.g., *substances*, *properties of substances,* or *direct causal events* rather than *constraint-based interactions*). Student use of substance-based predicates such as "blocks", "contains", "moves" instead of interaction-based predicates such as "transfers, "occurs simultaneously", and "is in equilibrium" provided evidence for their claim (Slotta, Chi, & Joram, 1995).

Chi's instructional remedy involved replacement strategies: (a) first provide *direct instruction* about the new ontological category and its general properties; and then (b) directly teach students that the concept in question is a member of the new category. Instruction also had a "domain-general" flavor: for example, students were taught about the new category of constraint-based interactions in the context of air expansion and liquid diffusion, and then asked to apply it to learning about electric current (Slotta & Chi, 2006). Finally, to prevent students from developing a faulty ontology for the new concepts, she recommends “expunging” material-based language and analogies in both teacher explanations and texts.

In contrast, the theory change proponents viewed the development of ontological categories as part and parcel of theory change. They assumed greater variety in the ontological categories available to the student and took a *transformation* rather than *replacemen*t view of change. Precursors are built on via multiple coordinated changes in content, epistemology, and representational tools. As a result, elements of the naïve ontology are not expunged, but are reanalyzed, integrated and explained within the emerging theory.

For example, Nersessian (1989) used her analysis of the development of “an inertial frame of reference” in the history of science (from medieval impetus theorists to Galileo to Newton) to inform her understanding of the structure of student ideas about force and motion and how students might be similarly led to construct an understanding of Newtonian ideas. She focused on changes in an entire conceptualization that includes multiple linked concepts. In contrast to Chi, she proposed a richer set of everyday ontological concepts (e.g., the medieval view includes categories of *place*, *process*, *motion, state, property, space, and body*), and argued that the construction of Newtonian ideas involves *many* ontological shifts (e.g., motion shifts from a *process* to a *state* like rest, and concepts originally conceived of as *propertie*s such as force, heaviness, and speed become reanalyzed as *relations*; other categories, such as *place* and *process* are no longer important in the revised conceptualization). For her, ontological shifts are difficult not because students lack the top-level categories but because “abstract entities need to be constructed….that only exist in mental models. For example, a Newtonian object is a point mass moving in an idealized Euclidean space” (p. 178). Thus, just as Galileo used thought experiments and limiting case analysis to help his colleagues construct new abstract representations, so too should teachers help students develop and use a repertoire of “abstraction techniques” to bridge from their everyday intuitions to more precise quantitative models.

Wiser and Amin (2001) provided another detailed account of the ontological difficulties students face and how they should be handled from a theory change perspective. The central ontological categories they consider are heat as *hotness* vs.

exchanged energy, both domain-specific ontological categories. They argued students' difficulty is not with understanding the energy exchanges that occur among colliding particles, but in recognizing their relevance to their concept of heat. Their multi-pronged instructional approach, therefore, first works to *enhance* student understanding of these energy exchanges via computer modeling activities, before explicitly contrasting the scientists' definition of "heat" as "exchanged energy" with students' idea that "heat" is inherently hot. Rather than ignoring students' everyday concept in their teaching, they work to help students re-analyze hotness as a perceptual, rather than objective property, and to see how their perceptual experiences can be explained in terms of the interaction of their perceptual system with physical variables. Like Chi, however, they regard the ontological stumbling block as important and needing explicit attention before addressing others topics in thermodynamics such as the differentiation of heat and temperature and the quantification of heat.

In contrast to these researchers, diSessa (1993b) was more skeptical about whether novices have any ontological categories or commitments, at least in the area of naïve mechanics, and if they do, whether they are that constraining. More recently, however, knowledge-in-pieces researchers have begun to theorize about the "ontological resources" of novices, and ontological classification has been reexamined from a knowledge-in-pieces perspective. We discuss this new work in our review of Phase Three research.

Epistemology

In Phase One, the focus was on highlighting *domain specific cognitive elements* at variance with the ideas of scientists and the challenges they posed for science learning. The ways limitations in students' general *metacognitive* capabilities pose challenges for content learning were hinted at, but largely unexplored. Instead, children's lack of meta-conceptual knowledge and skill was used to explain poor performance on various tasks despite substantial conceptual knowledge and reasoning skills being in place.

In Phase Two, researchers began to explore whether known developments in metacognitive capabilities (including epistemological beliefs) might be implicated in the process of conceptual change itself. The assumption was that greater understanding of the processes of knowledge construction enables the learner to become more aware of her changing conceptions and take control of the learning process. Developing greater epistemological understanding of science had long been an important, independent aim of science education, but now a new reason its development might be important emerged – promoting conceptual change itself.

As in many aspects of research on conceptual change, key terms are used in a variety of ways. Briefly, we take "metacognition" to be a broad term that encompasses more specific types of knowledge and strategies that take any aspect of cognition as an object of thought. These include thinking about concepts (metaconceptual), memory (metamemory), language (metalinguistic), diverse learning processes (memorizing, understanding), and knowledge (epistemology) among others. The last - epistemology - is particularly important to clarify because it has been seen as potentially central in the study of conceptual change. "Epistemology" refers to that aspect of metacognition that deals specifically with the nature of knowledge including its sources, its structure, its justification and limits (Hofer & Pintrich, 1997; Sandoval, 2005). Metacognition (including epistemology) can also be categorized in terms of its declarative (e.g., beliefs) and strategic (e.g., monitoring, self-regulation) aspects (Brown, 1978; Flavell, 1976).

Metacognitive knowledge and strategies can be studied from early childhood and there is a vast developmental literature examining its beginnings and transformations (see Kitchener, 1983; Kuhn, 2000 for reviews). Children's capacity for simple metacognitive reflection and monitoring is present in the preschool years, but greatly expands in elementary school when comprehension monitoring improves and learning becomes more strategic (Kuhn, 2000). In contrast, most work on epistemic cognition focuses on adolescents and adults, because it is assumed to be a "late" aspect of metacognitive development. Although even preschoolers make some distinction between "knowing" and "believing' and hence have some resources for developing epistemological beliefs about knowledge and its justification (Montgomery, 1992), schools typically present science as a "rhetoric of conclusions" (Schwab, 1964), affording little opportunity for students to develop more sophisticated epistemological views of science. Indeed, it is common for middle and high school students to have "knowledge unproblematic" views of science (Carey & Smith, 1993), with more sophisticated epistemological views only emerging in late adolescence and the college years, if at all (see Hofer & Pintrich, 1997, for review). Studies show that K-12 students think the goals of science concern simple description of what happens rather than deeper explanation (Carey, Evans, Honda, Jay, & Unger, 1989; Driver, Leach, Millar, & Scott, 1996). They think of experiments as finding out "what works" instead of as testing competing explanatory hypotheses (Carey et al, 1989; Schauble, Klopfer, & Ragavan, 1991) and of models as concrete replicas rather than as tools for the development and revision of theories (Grosslight et al., 1991). Here, we review literature that explicitly connects epistemological beliefs and conceptual change.

How might epistemological beliefs impact conceptual change? First, they may *directly affect* what students pay attention to in a situation (Stathopoulou & Vosniadou, 2007a). For example, students who think science involves only *description* may be more likely to focus on isolated or salient facts, whereas those who think it involves *explanatory hypotheses and theories* may look for organizing principles and patterns of relationships. Students who think science is *certain* and *unchanging* may avoid thinking about data that conflicts with their ideas, whereas students who think theories develop and change in response to disconfirming evidence may embrace such anomalies as a chance to learn something new.

Second, students' epistemological beliefs may have *indirect effects* through activating *goals*, which in turn elicit *strategie*s that promote or impede learning (Stathopoulou & Vosniadou, 2007a). Some strategies might affect learning in general ways. For example, the belief in simple knowledge may activate the goal to *memorize* information, which elicits superficial processing strategies such as rote rehearsal; in contrast, the belief that knowledge is complex may activate the goal to *understand* information, eliciting deeper processing strategies (e.g., making connections, integrating ideas). Other goals and strategies may be more specific to conceptual change in science. For example, in the classic conceptual change model of Strike and Posner (1985, 1992), students need to activate goals of identifying competing claims, monitoring their intelligibility, and competitively evaluating them based on their fit with other ideas, valued epistemological standards, and new research evidence.

Finally, there may be *interactive effect*s: whether epistemological assumptions support or impede learning may depend upon instructional context. For example, a classroom that is supportive of conceptual change may mitigate the negative effects of a less favorable personal epistemology (and even serve to develop more constructivist views), while traditional learning environments may exacerbate the differences.

A number of *correlational* studies have shown links between more sophisticated epistemologies and deeper conceptual understanding in particular domains. For example, Songer and Linn (1991) found that after an innovative unit on thermodynamics, middle school students who held dynamic rather than static views of science were more likely to have differentiated heat and temperature. Stathopoulou & Vosniadou (2007b) found that 10th graders with more sophisticated epistemological views about the structure, construction and stability of physics knowledge scored higher on the Force and Motion Conceptual Evaluation instrument after a traditionally taught physics unit. Using in-depth interviews with university physics students, Hammer (1994) found a strong relation between more constructivist epistemological beliefs (focusing on coherence, concepts, and independent effort) and deeper physics understanding. May and Etkina (2002) found that college students who started with low scores on the Force Concept Inventory, and who made dramatic learning gains had more constructivist ideas about what and how they were learning and the coherence of physics knowledge (as expressed in weekly reflection journals) than a comparable group at pretest who made little gain.

Case studies and experimental designs provide stronger evidence for the causal connection between epistemology, reflection on learning, and conceptual change. Some case studies have outlined mechanisms by which epistemological views may *limit* the physics learning of otherwise capable high school or college students. For example, some students expect that science relies only on formal reasoning and therefore do not think conflicts between formal and informal reasoning need to be reconciled (e.g., Hammer, 1994; Lising & Elby, 2005). Some research has sought to understand the processes by which more sophisticated epistemologies and conceptions of learning could be developed to *support* conceptual change. For example, Sister Gertrude Hennessey designed an entire elementary school science curriculum to help students develop their ideas about many challenging science topics, by engaging them in cycles of testing and revising their ideas to meet emerging classroom epistemological standards (e.g., clarity, generalizability). Students also learned to evaluate the changing status of their and others' ideas using the language of Strike and Posner's conceptual change model ("intelligibility", "plausibility", and "fruitfulness"). Her students not only developed more sophisticated constructivist epistemological views of science and learning (Hennessey, 2003, Smith et al., 2000) but also used those as tools to develop greater conceptual understanding of difficult science content such as Newton's laws of motion (Beeth, 1998).

Experimental studies at the elementary, middle school, and college levels provided evidence that "enriching" good curricula either with written reflective self-assessments or explicit attention to epistemological issues enhanced students' metacognitive understandings and conceptual change gains compared to outcomes observed for *those same curricula*r *experiences* without those enhancements. For example, Mason and Boscolo (2000) added "writing to learn" activities to a best practices 4th grade unit about plant growth, nutrition, and photosynthesis (e.g., students learned to regularly use writing to reflect on what they learned, express doubt, make predictions, and compare new explanations with previous ones.) Students in the writing to learn class not only developed greater meta-conceptual awareness of the process of conceptual change, but also made more progress on conceptual understanding than a control classroom that had the same unit without the writing activities. Reddish and Hammer (2009) found that a redesigned college physics course that emphasized "learning how to learn physics" (building coherence, thinking in terms of mechanisms, considering implications of assumptions) in addition to other best practices not only enhanced students' epistemological expectations, but also produced better pre-post gains on the Force Concept Inventory than previous versions of the course. Finally, White and Frederiksen (1998) studied multiple classes of 7th to 9th grade students, where students investigated force and motion through constructing a progressive series of models using innovative software. Half the classes also engaged in repeated self-assessment (using explicit criteria related to understanding science content, process, and habits of mind), while the other half did not. Those classes with self-assessment demonstrated better gains on measures of understanding of inquiry processes and on one of two physics knowledge measures. There was also evidence students' understanding of inquiry contributed to their learning of physics content in this curricular environment.

In sum, there is a convincing body of research establishing a connection between epistemological sophistication and conceptual change. Although more needs to be learned about what aspects of epistemology are most important, under what conditions, and through what mechanisms, conceptual change is promoted by encouraging students to: (a) reflect on the development of their own ideas in situations where they are engaged in authentic knowledge construction practices, (b) develop shared norms and epistemological standards for evaluating ideas, and (c) pay attention to anomalies or inconsistencies between formal and informal methods and work to resolve them. Most studies, however, have focused on force and motion. Concept learning in different domains may make some distinctive epistemological demands (e.g., the relation between formulas, concepts and laws is critical for force and motion; the ideas of explanatory model, macro and micro levels of description and emergent processes may be more important for atomic-molecular theory). Exploring these potential interactions with science domain is central to the more systemic approaches considered in Phase Three.

Models and modeling

Phase Two research also began to examine the role of models and modeling in the process of change. We consider a *model* to be a structural analog of a thing or a process. A *scientific* model is a simplified representation of a natural object or phenomenon that captures its central structural relations. A model can be internal, in the form of a *mental* model or external, embodied in various types of representations (e.g. diagrams, three-dimensional objects). We consider *modeling* to be those processes that lead to the construction of models. An example is analogical reasoning, which involves the use of a familiar, well-understood (source) domain of knowledge as a basis for improving understanding of a less familiar (target) domain.

The 1980s saw emerging interest in models and modeling in a variety of fields. In cognitive science, it was suggested that reasoning, even logical reasoning, was grounded in analogical mental models (Johnson-Laird, 1983) and that analogical structure-mapping allowed the construction of novel understanding via the transfer of relations between domains (Gentner, 1983). In history and philosophy of science, there was interest in the role of models in representing scientific theories (Giere, 1988) and modeling in novel theory construction (Nersessian, 1992). In science education, the construct of mental model was used to characterize some student conceptions, and analogies had been recognized as instructional tools for some time (see Duit, 1991 for a review).

We focus here on work characterizing the role of models and modeling in the *process* of conceptual change and instruction, tackling the following themes: (1) using visual representations and concrete situations in guiding students' construction of mental models that deepen understanding; (2) considering the appropriate level of abstraction at which to identify entry points and the appropriate sequencing of models in instruction; (3) using multiple, coordinated models that captured different aspects (both qualitative and quantitative) of scientific concepts; (4) presenting students with ready-made models versus engaging them in model construction; (5) attending to students' epistemological sophistication as a prerequisite for, and outcome of, instruction using models and modeling. Our review highlights these key themes but not separately, because individual studies often addressed more than one theme.

Brown, Clement and Minstrell (Brown & Clement, 1989; Clement, 1993; Minstrell, 1982) sought to build student understanding of Newtonian concepts using intuitive knowledge elements they called "anchoring intuitions" – e.g. students' understanding of normal forces was grounded in their intuitions that a spring exerts an upward force on an object placed on it. This was an intelligible analog of the less transparent (target) situation of a table exerting a normal force on a book resting on it. But students often found the analogy between the two situations implausible. Therefore, Brown and Clement (1989) proposed using a "bridging analogy" that retained key features of the "anchoring intuition" but resembled the target situation more closely (e.g., a book on a thin, and thus slightly springy, plank of wood). The rationale for their approach was that anchoring intuitions and bridging analogies supported students' construction of analogical *explanatory* models of the target situation that incorporated key intuitions (e.g. modeling a wooden table as made of microscopic springs exerting upward forces on a book placed on it).

The work of Smith (Smith et al. 1992, 1997) and Wiser (1995; Wiser & Amin,

2001) was based on the idea that certain concepts - e.g. heat/temperature and weight/density - are differentiated in science but undifferentiated in the learner before instruction. In both cases, a learner possesses an undifferentiated perceptually based concept (i.e., "hotness" and "felt weight") and computer-based visual representations were designed that could embody the scientific concepts and the relationships between them and be intuitively compelling. For example, the heating of an object could be represented using a variety of models, such as (a) the number of E's entering a rectangle/object from a hotplate and (b) the number of E's per molecule with numbers inside partial circles representing the molecule. The models embodied the distinction between the extensive concept of heat (total E's added) and the intensive concept of temperature ("packedness" of E's per molecule). A "grid-and-dots" model captured the extensive/intensive distinction between weight and density with dots representing weight units, boxes representing volume units, and dots per box representing density. This model was at the center of programs that provided progressively more complex modeling possibilities embedded in investigations of density of materials, floatation, and thermal expansion. The distinct visual representations of key quantities encouraged metaconceptual discussion of the contrasting meanings of terms and the nature of models as well as simplified the quantitative aspect of the domains in question. Both approaches supported the differentiation of key concepts.

In related work, White (1995; White & Frederiksen, 1998) designed an inquiry-oriented, computer-based learning environment within which students engaged with multiple models to investigate forces and motion at different levels of abstraction. The research made the case for the value of models at an *intermediate level* of abstraction as an entry point for instruction, as well as the progressive construction of models of more complex microworlds (e.g., motion without gravity before motion with). Central to the design was building on and extending student intuitions to make sense of the motion of a dot in a simulated Newtonian micro-world. Students used a joystick to impart "impulses" that changed the speed of the dot by one unit with each impulse. The speed of the dot was represented via points left in the wake of the movement of the dot. The "dot-print" representation was at an intermediate degree of abstraction in between the immediacy, yet complexity of real object motion and mathematical formulations of Newton's laws. In this way, students could construct qualitative understandings and formulations of laws governing a Newtonian world that were easier to align with mathematical representations. This learning environment was successful in developing middle school students' conceptual understanding of Newtonian mechanics, as well as their inquiry and modeling skills and understanding of laws.

The research reviewed so far made use of *ready-made models* provided by researchers. Although these models were designed to be interpreted both qualitatively and quantitatively, qualitative reasoning was seen as an initial step to address problematic misconceptions to be followed by mathematization. One problem with ready-made models, noted by Wiser and Amin (2002), is that while students might understand the analog models themselves, they do not readily map them onto their existing concepts (e.g., heat/temperature) that are being targeted by instruction. A different line of research has approached science learning from the perspective that model *construction* and mathematical reasoning are central to scientific practice and so should be central to the practice of science education as well (Lehrer & Schauble, 2000; Lehrer, Schauble, Carpenter & Penner, 2000; Lehrer, Schauble, Strom & Pligge, 2003). Lehrer and Schauble (2000) proposed a taxonomy of models that can be seen as a possible developmental corridor with students progressing gradually to more abstract models over extended (multiyear) periods of time: three dimensional microcosms (e.g. a globe); maps and other 2-dimensional representations; syntactic models (e.g. probability models); and hypothetical-deductive models (e.g. kinetic model of gases).

In this model *construction* approach, students are given design or inquiry tasks driven by a goal or question. For example, in Lehrer et al. (2000), second graders explored the motion of objects rolling down inclined planes in the context of designing Lego cars that go down a track "as quickly" or "as slowly" as possible. As they worked, children encountered conceptual obstacles and teachers guided the students in their attempts to solve these problems, with an emphasis on the use of inscriptions of various kinds. The conventions of representation and modeling were not taught directly but emerged over the course of student work. Lehrer et al. argue that presenting ready-made inscriptions or models rather than expecting students to construct these when the need arises will often result in students misunderstanding both the general representational function of the model and the specific mappings between the model and the entities it represents.

Because the scientific topics addressed in this approach are motivated by student questions that emerge during instruction, many challenging conceptual domains have not been studied from this perspective. But Lehrer et al. (2003) have shown how this kind of modeling instruction can drive fifth graders' differentiation of weight and density, reaching a level of understanding in a difficult domain often found challenging to middle-school students. They argue that if students develop strong mathematical concepts of measure and similarity first, this can support more sophisticated modeling of physical phenomena and drive conceptual change.

One way to contrast the ready-made models versus the model-construction approach is in terms of the simplicity or complexity of the quantitative reasoning targeted and the time scale of interventions. The ready-made models approach involves interventions on the order of months and aims to simplify quantitative reasoning, focusing instead on supporting learners in constructing deeper theoretical understanding of the domain in question, using existing mathematical knowledge. The model-construction approach, involving multiyear interventions, aims to engage students in complex quantitative reasoning that is grounded in conceptual understanding of measure. No research has explicitly evaluated the relative effectiveness of ready-made models versus model construction approaches. While such comparison might yield interesting results, more worthwhile might be the comparison of affordances of the two approaches for future learning. We discuss this line of work on long term learning progressions in our review of Phase Three research.

In sum, research on models and modeling made progress in highlighting the role of analogical restructuring and the strategic recruiting of intuitive knowledge in the process of conceptual change. It also drew attention to the relationship between qualitative and quantitative understanding. In addition, it attracted researchers' attention to the interplay between conceptual change, processes of model-based reasoning and epistemological understanding about modeling. Phase Three research extends this pioneering work by developing more explicit accounts of the format and interaction of internal and external representations, social interaction, and epistemological development.

Social interaction

Phase Two research on conceptual change also began to examine the role of social interaction in the process of conceptual change. Our review includes *only* research that has addressed social interaction processes *in relation* to scientific concept learning specifically. (See Scott et al., 2007 for a review that takes a broader perspective on social processes in science learning.) Three (complementary) perspectives are considered. Research from a *sociocultural perspective* on learning (Vygotsky, 1978; Wertsch, 1991) assumes that internalization of knowledge results from two types of social interactions: scaffolding provided to learners by those more knowledgeable and knowledge jointly constructed by peers. The goal of this research is to show that social interaction (in general) enhances concept learning and to describe the kind of scaffolding that allows students to participate in effective discourse. Research from a *discourse analysis perspective* sought to describe the details of communication occurring in these interactions that allows *convergence* among diverse ideas. In contrast, research from a *Piagetian (1995) perspective* examined the role of cognitive conflict arising from interaction between peers with different ideas in a domain, challenging the assumption that internalization was the sole mechanism by which social interactions affects conceptual change.

Research on science concept learning conducted from a sociocultural perspective emphasizes that scientific concepts are learned not through direct experience but through guidance in appropriating a way of seeing the world embedded in a symbolically constructed reality (Driver, Asoko, Leach, Mortimer & Scott, 1994). For example, scientists think about/see/analyze the world in terms of abstract and symbolically represented theoretical concepts. Further, although they explicitly reflect on “theory,” “predictions,” “results” and their relations, these analytic categories are cultural constructions that are not obvious to young students. Driver et al. (1994) argued that through classroom discourse students can be “scaffolded” into a scientific way of talking about (and thereby “seeing”) the world.

A prominent example of research that attempted to so structure the discourse of science classrooms and examine its effects on concept learning is Herrenkohl, Palincsar, DeWater and Kasawaki (1999). In this study, upper elementary students were assigned roles to scaffold inquiry and participation in scientific thinking practices during investigations of flotation and sinking. *Procedural* roles structured students' efficient completion of the small group investigations and *audience* roles (e.g. questioners, commentators) focused on particular tasks (e.g. checking predictions and theories, summarizing results and evaluating the relationship between predictions, theories and results) during whole group discussion. In this way, engaging in a complex task was broken up into parts, and students were encouraged to focus on the particular kinds of thinking expected of them. Analysis of transcripts of classroom conversations shows the progress students made in appropriating these roles over the 10-week unit. Moreover, pre- and post-tests revealed dramatically improved conceptual understanding of floatation (that drew on an understanding of density) and better explicit understanding of predictions, theories, scientific problem-solving and how scientific ideas are evaluated.

Other sociocultural researchers have explored the effect of peer interaction on concept learning in a series of experimental studies using the Hypothesis-Experiment-Instruction (HEI) method. In one study (Hatano & Inagaki, 1991), a control group of students was asked to select from a number of possible predictions about a physical phenomenon and were then presented with a text providing an authoritative answer. An experimental group included the additional component of asking students to discuss their predictions with one another before being presented with the correct prediction. Significantly more students in the experimental condition, which included discussion among peers, produced better quality explanations than the control condition.

If social interaction contributes to concept learning, this connection may be mediated by the details of communication between interlocutors. During Phase Two, some researchers began to examine the details of communication, highlighting the features of communication they thought were most relevant to understanding the process of concept learning. For example, Pea (1994) suggested that concept learning is more likely to occur when interlocutors transform their understandings together as they negotiate interpretations of each other's utterances trying to arrive at common ground.

Pea also suggests that effective science concept learning will occur when learners' communication is modeled on that of scientists, involving the sharing of multiple interpretations of phenomena, and requests for clarification from each other about the meaning of representations.

Other researchers adopted a similar discourse-oriented perspective on conceptual change (Duit, Roth, Komorek & Wilbers, 1998; Roschelle, 1992), drawing on methods of conversational analysis (Garfinkel & Sacks, 1970; Goodwin & Heritage, 1990) to describe the types of *conversational moves* occurring when students engage in collaborative learning activities. For example, Roschelle (1992) suggested that interlocutors' understanding will converge as a result of conversational moves related specifically to conceptual change (e.g. constructing representations of the key entities and processes underlying natural phenomena; and coordinating metaphors to interpret the representations) and others that help establish convergence (e.g. engaging in cycles of "displaying, confirming and repairing" meanings and applying increasingly higher standards of evidence for establishing convergence in the meanings constructed by participants). Overall, the conversational interactions seen by these researchers as relevant to conceptual change align with the audience roles of questioning and commenting that Herrenkohl et al. (1999) included in their intervention, but focuses more on the dynamics of negotiating the interpretation of representations in contrast to Herrenkohl et al.'s emphasis on the broader structures of participation and participant roles.

The research reviewed so far assumes that students construct novel conceptual understandings by *internalizing* knowledge provided by teachers or jointly constructed with peers. A different body of literature took as its starting point the Piagetian (Piaget, 1995) view that conceptual conflict is an important driver of knowledge change. Howe and colleagues considered the possibility that individual, *internal* constructions provoked by disagreements during interaction might be the source of change, rather than joint constructions. Carefully controlled experimental studies bore out this hypothesis in the context of elementary children's collaborative inquiry into different topics, including motion down an inclined plane (Howe, Tolmie & Rodgers, 1992). Student gains in conceptual understanding were greater when students were placed in groups with different (rather than similar) ideas about the topic. Moreover, while significant correlations were found between group level performance and degree of agreement within a group, there was no significant correlation between "within group change" and individual student gains for student groups whose members had different ideas. This research also identified domain differences, with private conflict resolution being more important in physics than in biology (Williams & Tolmie, 2000). More recent research in this tradition has begun to examine more closely the relative importance of joint and individual constructions and the interactions between group level and individual level mechanisms (Howe, 2009; Howe, McWilliam & Cross, 2005). An interesting finding emerging from this literature is the connection between unresolved conflict in group interactions and long term conceptual gains.

In sum, the research just reviewed suggests that a variety of mechanisms are at work, mediating the influence of social interaction on conceptual change. Effective concept learning in the context of social interaction seems to require carefully thought out scaffolding of scientific discourse on the part of teachers. However, the research also suggests that we must be cautious in assuming internalization of group products as the sole mechanism of individual concept change in the context of social interaction. Individual cognitive constructions driven by group level conflict might also be an important (if not primary) mechanism of change in some domains. Overall, research in this area suggests that there are important connections between the roles of social interaction and epistemology in conceptual change, connections that future research will need to explore.

Phase Three -- Emerging Systemic Perspectives on Conceptual Change

In this final section, we highlight emerging *systemic* perspectives on conceptual change and suggest directions for future research. Some researchers use a particular approach to systemic thinking - e.g. Brown and Hammer (2008) use dynamic systems theory. However, we use the term "systemic" informally to capture a tendency among researchers to understand conceptual change in terms of multiple interacting elements, often at different levels of analysis. We begin by describing attempts to understand concepts and conceptual change from various systemic perspectives, pointing out implications for instruction. Next, we describe research that has investigated instructional designs based on a systemic understanding of conceptual change.

Understanding concepts and conceptual change from systemic perspectives

We frame our review in terms of four foundational themes in cognitive science. First, concepts are grounded in multiple image-schemas (abstractions from sensorimotor experience) and imagery (reenactments of perceptual experience). Second, the use of language and other external symbolic systems overcome the limitations of image-schematic representations and imagery. Third, propositionally expressed concepts can be understood as language-like symbols that participate in networks of beliefs. This idea resolves some tensions among competing accounts of conceptual change. Fourth, the conceptual knowledge of young children and laypersons is sparse. But because this sparse knowledge is associated with epistemological beliefs that more specific knowledge exists, the source of which is often other people, it supports further learning. Together, these four sets of ideas reflect an increasingly systemic turn in cognitive scientists' thinking about concepts and conceptual change.

Concepts and conceptual change are grounded in perception and action. We begin by clarifying some key constructs. As these have occupied philosophers and psychologists for centuries, we will only clarify how we use them here, drawing on extended treatments of others (Barsalou, 1999; Carey, 2009; Mandler, 2004). We assume *perception* to be an automatic process, carried out by innately specified systems that provide the mind with analogical representations of the here-and-now, resulting in sensori-motor experience. What makes these systems perceptual is that they *automatically* provide the mind with *rich* representations of entities in the outside world. We understand a *conceptual* representation to be one that can be productively combined with others, supports inferences about real and imagined entities and can be articulated with language. Thus, a conception is accessible to different aspects of cognition. We assume that innate *perceptual* processes can generate some *conceptual* representations of objects, agency, number and cause, referred to as "core cognition" (Carey, 2009).

The construct *image-schema* captures the idea that through repeated sensorimotor experiences and processes of selective attention, commonalities across those experiences are extracted, forming more schematic structures. Image-schemas are analogical (iconic) representations that structurally resemble the objects and events represented in perception. For example, an image-schema of containment, with the components *inside*, *outside*, and *a boundary separating the two*, can be abstracted from many similar experiences of putting objects in, and removing them from, various containers. Despite being analogical representations, image-schemas are *conceptual* in the sense clarified above. While conceptual, they are not propositional, language-like representations, with an arbitrary symbolic relationship to what they represent, but resemble their referents. However, they are not to be equated with imagery, analogical “movie-like” reenactments of perceptions/actions in the mind’s eye, invoked in the absence of the actual objects and events of the world they represent. Because imagery is un-analyzed and holistic, it cannot on its own support productive conceptual combination, inferences and articulation with language.

There is considerable agreement on the importance of image-schematic representations, especially in *preverbal* conception (Barsalou, 1999; Carey, 2009; Mandler 2004). However, there is disagreement regarding how image-schemas are constructed. While Mandler (2004) suggests that the processes of abstraction and selective attention are sufficient, Carey (2009) has persuasively argued that innate, core conceptual representations are needed to constrain the process of abstraction from sensorimotor representations. It has also been suggested that adult concepts, including abstract concepts, are represented in terms of multiple image-schemas. For example, Barsalou and Wiemer-Hastings (2005) have suggested that the difference between concrete and abstract concepts is not in the *format* of the concepts’ representation, but in complexity. They provide evidence that whereas the representations of situations or events are backgrounded in the representation of concrete concepts, they are foregrounded in the case of abstract concepts. Another proposal, based on analysis of patterns of language use, is that many abstract concepts are understood *metaphorically* in terms of image-schemas (Lakoff & Johnson, 1980, 1999). The claim is that systematic conceptual mappings exist between abstract and experiential *conceptual* domains ("conceptual metaphors") - e.g. states are construed as possessions (as in "He *has* a headache"); time as a resource (as in "Time is *running out*"). This view of abstract concepts as grounded in perception and action has also contributed to accounts of scientific concepts and model-based representations of scientific theories and reasoning (Clement, 2008; Nersessian, 2008; Thagard, 2012).

This idea that concepts are grounded in image-schemas extends to science concept learning research in Phase Three, as researchers continue use of the constructs p-prim and mental model. Most researchers drawing on the notion of p-prim treat it as an image-schema (e.g., Ke, Monk & Duschl, 2005; Sherin, 2006), which seemed to be the intended sense in the most explicit and extended account of the construct (diSessa, 1993a). While some have used the construct without a strict image-schematic interpretation (e.g. D. Clark, 2006), we believe that it is useful to so limit the interpretation of p-prims. This emphasizes their origin in perception and action, and clearly distinguishes them from other knowledge elements of different format, such as propositionally formulated beliefs. Assuming that scientific concepts are grounded in image-schematic p-prims was a key contribution of the knowledge-in-pieces view described earlier, and continues to be an important assumption in much of Phase Three research, consistent with the cognitive science literature more broadly.

The notion of a mental model also continues to be used. While earlier research was not always explicit about the representational format of mental models (Gentner & Stevens, 1983), recent work has been more explicit in viewing mental models as consisting of imagistic simulations of perceived object and events, interpreted in terms of multiple image-schemas (Clement, 2008; Nersessian, 2008). Since they are constituted by image-schemas, mental models are *conceptual* representations. Methods are now being explored to provide evidence of the format of mental models and their image-schematic and imagistic constituents, relying on the analysis of gestures and drawings used by scientists and students as they engage in creative analogical and extreme-case reasoning and thought experiment (Stephens & Clement, 2010). Another method of identifying image-schematic representations of relevance to science learning focuses on the analysis of the language of science from the perspective of the theory of conceptual metaphor

(Amin, 2009; Amin, Jeppsson, Haglund, & Strömdahl, 2012; Jeppsson, Haglund, Amin & Strömdahl, 2013).

What are the instructional implications of the assumption that scientific concepts and reasoning might be grounded in image-schemas and imagistic simulation? Because multiple image-schemas need to be activated, organized, and re-organized during science concept learning in ways that are highly sensitive to context, there is no "quick tell" in concept formation. This implies the importance of presenting concepts in *contexts-of-their-use*. While this idea has long been a staple of 'reform' science curricula, recognizing the importance of a complex, nonverbal component to concept formation indicates that this approach is not just desirable but *necessary*.

In addition, while mental models have been found to ground understanding of scientific concepts, other representational resources are needed. Since most scientific models include very abstract and often quantified entities and processes, they will need propositional symbol systems (such as language and equations) to represent them (see next subsection). Recognizing that the image-schemas and imagery that constitute mental models are shared by learners and scientists suggests that scientific models with more iconic components are likely to be more accessible entry points for instruction. For example, Lehrer and Schauble (2006) have argued that initial models based on *resemblance* are important starting points for elementary school students' modeling; with appropriate instruction, students can construct progressively more sophisticated models drawing on language or equations. Moreover, research (Wilensky & Novak, 2010; Wilensky & Reisman, 2006) has explored the use of "agent-centered modeling" in supporting understanding of emergent processes in many domains (e.g., electricity, population biology), a widely recognized instructional challenge (Chi, 2005; Perkins & Grotzer, 2005). Students first create agent-based models consisting of objects with specific properties; then they run the models on computers that use visual representations to help students "see" the consequences at another level (the emergent properties of aggregates).

A final instructional implication is based on identifying the set of conceptual metaphors that construe a given scientific concept. Once these are known they can guide the design of visual representations that aim to foster conceptual change (Amin, 2009;

Scherr, Close, McKagan & Vokos, 2012) and guide the strategic selection of particular analogies (Amin et al., 2012; Niebert, Marsch & Treagust, 2012). For example, Amin et al. (2012) argue that the Entropy As Freedom analogy is more likely to trigger the application of productive intuitive, image-schematic knowledge than Entropy As Disorder, because the former is more consistent with the conceptual metaphors conventionally used in science to construe entropy.

The picture that emerges from the literature reviewed in this subsection is that the concepts of both learners and scientists are represented in terms of multiple perception- and action-based image-schemas and their use in reasoning employs imagistic simulation. This recognizes a degree of continuity between the learner and the scientist, and suggests useful entry points for instruction.

The limitations of image-schemas and imagery can be overcome with external (especially propositional) representations. Both the content and format of image-schemas and imagery are limited in the kind of conceptualizing and reasoning they support. Language and other representational tools (e.g. equations) play an important role in expanding the possibilities of the human conceptual system (A. Clark, 2008). Research in developmental psychology suggests that learning *language* can both shape the formation of conceptual categories (Mandler, 2004; Waxman & Markow, 1995) and provide a basis for the construction of novel concepts that would not be possible without language (Carey,2009). According to Carey, a sentence first functions as a shallowly interpreted symbolic *placeholder* (e.g. "Matter is that which has weight and occupies space"), which then gets interpreted through modeling practices that draw on image-schematic and other conceptual resources. It has also been suggested that understanding conceptual development will involve understanding how language can guide cross-domain mapping (e.g. the domains of space and physical objects) and integration, using image-schemata from one domain to construct understanding in another domain (Gentner, 2003). Recent research on scientific understanding and reasoning has investigated the interactions within distributed systems of internal (mental) and external representations (e.g. diagrams, equations, language), both in characterizing scientific models (Giere, 2002) and in accounts of conceptual change in the history of science

(Nersessian, 2008).

Recent work in the knowledge-in-pieces tradition in science education has been incorporating more attention to propositional representations (diSessa, 1996; Levrini & diSessa, 2008; Sherin, 2001, 2006). diSessa (1996) lists nominal facts, narratives and committed facts (all propositional representations) as relevant to an account of the novice's understanding and reasoning about the physical world, in addition to more imagistic elements (p-prims, mental models). Nominal facts are statements appropriated from everyday discourse or formal instruction, which initially have little meaning to the learner – e.g. "Temperature is proportional to average kinetic energy." Narratives are sequences of shallowly interpreted propositions that describe a sequence of events and the objects that participate in them, such as the energy transformation narrative of a falling object. Committed facts are statements interpreted more fully (e.g. 'Moving something requires a force').

In a knowledge-in-pieces account of concept learning, nominal facts and shallowly interpreted narratives can be initially learned by rote, but play a role in guiding the strategic application of p-prims and other resources, functioning as placeholders for conceptual change (Carey, 2009). For example, Levrini and diSessa (2008) show that high school students struggled to make sense of two definitions of proper time in special relativity across contexts, but their assumption that these definitions should lead to the same conclusions guided their construction of a more general understanding of the concept. Cheng and Brown (2010) argue for the importance of integrating linguistic and imagistic representations. They found that elementary school children who relied only on intuitive knowledge when constructing explanations about magnets across a range of situations constructed fragile and fragmented models. Notably, the one student who developed and revised an explanatory model across situations had integrated both linguistic and imagistic representations and was meta-cognitively aware of her model building.

Adopting the conceptual metaphor perspective, Brookes (2006; Brookes and Etkina, 2007) has proposed that many analogical models that played a role in scientific concept formation are encoded in the language of scientists as conceptual metaphors, reflecting current and defunct models. Over time, scientists develop a tacit understanding of the strengths and limits of metaphorical models, and the appropriate contexts in which to reason with them. However, students may be misled by scientists' language. Indeed, Brookes and Etkina document some common and robust science misconceptions (including ontological misclassifications) that may originate in patterns of language students commonly hear. Part of the solution, they suggest, may be more care with the language used in instruction. However, given the implicit way in which metaphor pervades language, it might be more practical to have explicit discussions with students about scientific language and misleading ontological construals (Amin et al., 2012; Brookes and Etkina, 2007; Jeppsson et al. 2013).

Focusing on another type of propositional representation, Sherin (2001, 2006) provided evidence that "symbolic forms" mediate the interaction between physics equations and conceptual understanding while university physics students solve problems. Symbolic forms are pairings of conceptual schemata (many of which are image-schemas like p-prims – e.g. opposing influences) with general patterns of symbols in equations (e.g. □ - □) that are used to interpret equations. Sherin (2006) suggests that use of equations can actually guide the activation, reorganization and refinement of p-prims. More work is needed to understand how students develop these symbolic forms and the role they play in guiding the use of intuitive knowledge when using equations. Another issue for future work is the role of language in mediating between qualitative and algebraic understanding. Jeppsson et al. (2013) suggest that metaphorical language, in coordination with symbolic forms, plays such a mediating role. If so, one way to enhance students' construction and use of symbolic forms may be for instructors to talk aloud and model some of their processes of *interpreting* equations in the course of problem-solving.

The significance of this research on the role of external representations can be appreciated in relation to the criticism in early concept learning research of the traditional practice of 'leading' with definitions of new words, as that was seen as preventing students from activating meaningful conceptual resources. While valid, this critique may have led some to overlook the central role of linguistic and mathematic symbols in the construction of scientific concepts. Although the resurgence of social interactionist perspectives during Phase Two led to increased attention to student language and other forms of symbolization and inscription, the main focus was on the *discourse or inscriptional forms* themselves, rather than their interaction with internal conceptual resources. Future work will need to examine this interaction more closely.

Concepts as participants in versus constituted by beliefs: Resolving a tension. Earlier, we contrasted two perspectives on conceptual change: the "coherence" and "knowledge-in-pieces" perspectives. Recent developments have led to considerable convergence. However, the views continue to be contrasted in the literature, especially with regard to what concepts are taken to be. We argue that the apparent difference in how the two perspectives view concepts reflects a tension between viewing concepts as *participants in*, versus *constituted by*, beliefs. We suggest here that a view of concepts described by Carey (2009) helps resolve this tension and reveals considerable consensus in how coherence and knowledge-in-pieces perspectives view concepts.

We begin with some considerations on the nature of concepts relevant to the coherence versus knowledge-in-pieces debate. Earlier we clarified that image-schematic abstractions from sensorimotor experience are *conceptual* representations that support the construction of preverbal concepts. The more developed conceptual system also consists of concepts expressed propositionally. Indeed, all *scientific* concepts are of this type (as was implied in the previous subsection). Thus, our focus here will be on providing a precise characterization of what we assume a propositionally expressed concept (henceforth, "concept") to be. To Carey (2009), a concept is a language-like symbol that can participate in propositions relating it to other symbols. On her account, characterizing the *content* of that concept involves specifying two things: (a) those processes (both external and internal) that enable the concept to r*efer* to entities in the world and (b) the concept's inferential role, which is specified in terms of the network of propositions that the concept participates in. This view of concepts helps resolve the apparent tension between viewing concepts as participants in beliefs and as constituted by them. A concept per se, seen as a unitary, language like symbol, can participate in beliefs. The idea that concepts are constituted by beliefs refers to the *content* of the concept – that is, the way the concept functions and contributes to thought is specified by its role in a network of inferences and the mechanisms that establish what entities in the world the concept picks out.

Viewing concepts in this way helps us consider more carefully the differences between coherence and knowledge-in-pieces perspectives. As discussed earlier, from a coherence perspective, concepts, even naïve ones cannot be characterized in isolation (Chi, 2005; Smith, 2007; Wiser & Smith, 2013; Vosniadou, Vamavakoussi & Skopeliti, 2008). A concept is understood in relation to others in terms of a network of beliefs and conceptual change involves a set of interconnected changes leading to a different network. But conceptual change is usually envisioned as gradual because many changes in the conceptual system need to occur. What current coherence accounts add to Phase One research is that more elements are recognized as involved in the process of change - e.g., domain specific beliefs (both qualitative and quantitative), epistemic beliefs about what constitute appropriate sources of knowledge about entities in the world, models, and beliefs about the nature and function of scientific models.

From a knowledge-in-pieces perspective, naïve conceptual knowledge is believed to be fragmented, but contains many potentially useful knowledge elements. However, earlier work had not provided an account of the nature of *scientific* concepts in terms of readily available knowledge elements. The construct “co-ordination class” has now been put forward to address that gap (diSessa, 2002; diSessa & Sherin, 1998). A coordination class is a knowledge system with multiple constituents, including p-prims, mental models and beliefs. Its function is not categorization per se, which diSessa and Sherin (1998) suggest has been the main function attributed to concepts by psychologists, so much as reliably picking up information about an important invariant in the world. Some but not all scientific concepts are assumed to be coordination classes – candidates are those concepts that reliably pick out quantitative information (e.g. force or velocity). Having a coordination class involves possessing a structure that can adapt to different contexts of use such that information can be extracted consistently across contexts. Coordination classes are composed of two distinct types of components that differ in function: read out strategies (e.g., perceptual) that enable a person to identify instances of appropriate application of that class (e.g., establishing when it is appropriate to “see” force); and the causal net (a network of heterogeneous elements including p-prims, mental models, equations, and beliefs) that enable inferences that provide the desired information (e.g., the magnitude or direction of a force).

So how do the coherence and knowledge-in-pieces perspectives on concepts differ? diSessa (2002) suggests that while the knowledge-in-pieces perspective has put forward the construct of coordination class as an account of the *internal* structure of some scientific concepts, coherence views focus on networks of *relationships* between concepts within networks of beliefs. In a later review, diSessa (2006) formulated this difference in terms of the "nesting" of concepts within larger networks of beliefs. Coherence views provide accounts of scientific concepts as (tightly) constrained by the networks of beliefs that they are nested within. Although nesting is acknowledged as a feature of coordination classes (knowledge elements such as p-prims are nested within coordination classes), the constraints that arise between elements and levels are relatively weak.

We suggest that this difference dissolves in light of the distinction between a concept understood as a unitary language-like symbol and the content of a concept understood as its inferential role and the mechanisms that establish reference. Both coherence and knowledge-in-pieces proponents are really concerned with the *content* of concepts as defined above. This is clear in the case of coherence views, especially those that are explicit about being concerned about coordinated changes in networks of beliefs. Similarly, accounts of coordination classes also appeal to networks of beliefs relating concepts to each other when characterizing the causal net (e.g., the Newtonian Force coordination class includes the equation $F=ma$ (diSessa & Sherin, 1998); determining the magnitude of a force, F, implicates recognizing and determining magnitudes for m and a, which in turn can be given coordination class accounts). If we understand concepts in this way, the word "Force" or the symbol "F" (or some mental token representing both) which participates in key propositions within a causal net *is* the scientific concept of force; it is the *content* of the scientific concept in Carey's account that corresponds to the coordination class as a whole. It is this content that tells us what entities will be picked out in the world by the concept and what inferences it would support

Carey's account is also not incompatible with the knowledge-in-pieces claim that different elements are activated in different contexts. There is no a priori assumption that the same knowledge elements are activated every time a given concept (understood as a unitary, language-like symbol) is used. Thus, we suggest that the emerging consensus on the learning of scientific concepts is that it involves the gradual formation of increasingly organized *networks* of heterogeneous knowledge elements, including propositional representations such as language or mathematical representations, as well as image-schematic representations.

Pointing out this deep similarity in the view of concepts adopted by coherence and knowledge-in-pieces perspectives does not deny an important difference that is often highlighted - that they adopt different assumptions regarding the degree of coherence of naïve knowledge. However, this difference is really in the *degree* of coherence in *specific domains* of knowledge. Coherence views expect that small networks of beliefs and broad ontological presuppositions can constrain knowledge construction in specific domains, especially in early childhood (possibly guided by innate constraints). But as coherence researchers increasingly appeal to multiple, heterogeneous knowledge elements in the characterization of naïve understanding, the two views look increasingly similar, especially as some knowledge-in-pieces theorists have granted the possibility that novices may have small-scale networks of interconnected beliefs (Brown & Hammer, 2008). Moreover, coherence theorists increasingly acknowledge that the network of beliefs that constitutes naïve conceptual understanding is not as well organized as initially assumed and that learning will involve a substantial process of organizing and expanding its scope of application (see Vosniadou, Vamavakoussi & Skopeliti, 2008; Wiser & Smith, 2013).

This consensus view of concepts has an important instructional implication - that the curriculum should foreground *relations*, rather than focusing on concepts in isolation as is typical in traditional instructional units. Reorienting science curricula generally to focus on models and modeling addresses the need to emphasize relations (Lehrer & Schauble, 2006). However, this raises central questions about how decisions about sequencing and revisiting these relations should be made in specific domains. One constraint on sequencing has depended on what relations can be directly investigated more *concretely* via experimentation, and what ones have to be *inferred*. For example, as Minstrell (1984) argued some time ago, in teaching Newton's three laws, it was important to present the *second law* about the relation of force to acceleration *before* the first that asserts that no net force is needed to maintain constant velocity, because the former, but not the latter, could easily be demonstrated. This issue is at the heart of current curricular design studies exploring effective “pathways” for learning (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003), didactic theories (Andersson & Wallin, 2006), and work on long-term learning progressions (Wiser, Smith, & Doubler, 2012), to be discussed shortly in our review of new, systemically oriented research on instruction.

Expanding the scope of systemic thinking about conceptual change: ontology, epistemological beliefs, modes of construal and social interaction. Phase Two research identified ontological classification, epistemic beliefs and social interaction as influences on conceptual change. We revisit these influences again here highlighting recent efforts to examine these influences in more systemic terms.

The idea that conceptual change involves a process of ontological reclassification of concepts has been criticized recently by knowledge-in-pieces proponents (Gupta, Hammer, & Redish, 2010; Hammer, Gupta & Redish, 2011). They question whether the shift is from one static, stable ontological category to another, and whether certain ontological categories, often considered absent in the novice, are in fact absent. For example, the notion of emergent processes, as in diffusion, can be found in the intuitive appreciation of the idea that while crowds can be seen as moving in some direction at a global level, specific individuals can be moving in a variety of directions. Moreover, both learners and experts classify a given concept with considerable flexibility, often straddling multiple ontological categories. In response, Slotta (2011) has argued that experts may hold *parallel* ontologies for a concept, but only under exceptional circumstances, such as in the case of wave-particle duality in modern physics. Slotta also accepts that scientists may construe an abstract concept more concretely in terms of a material substance in informal or pedagogical contexts but will not treat this way of thinking as scientifically acceptable. As Slotta (2011, p. 157) puts it, “experts can still think of electric current as ‘juice’ squirting through a wire but would quickly acknowledge that such a substance does not actually exist.”

We find this to be an interesting debate, but one that would benefit from a broader theoretical framing in terms of emerging systemic perspectives. On the one hand, there is the assumption that abstract concepts are often grounded in informal, imagistic representations (as discussed earlier). The argument that experts sometimes talk metaphorically and reason about abstract concepts such as emergent processes as if they are material substances is consistent with this assumption. On the other hand, the emerging systemic perspectives on concepts and conceptual change alert us to the need to distinguish between conceptual knowledge and metacognitive beliefs *about* that knowledge. Some resolution of the debate between stable and flexible ontological classification might be possible by acknowledging that scientists know, *metacognitively*, that energy and entropy, are not material substances but still draw on substance-like metaphors when construing these concepts for particular purposes (Jeppsson et al., 2013). The distinction between *explicit* ontological stances and *implicit* ontological resources might be important if we are to understand the role of ontology in conceptual change from a systemic perspective.

The knowledge-in-pieces framework has also been extended to include epistemological elements, reflecting the systemic turn we are describing. Hammer and Elby (2002) identified many “epistemological resources” that even young children activate in learning situations. They organize them in four broad types: resources for understanding the diverse *sources of knowledge* (e.g. other people vs. direct perception); *epistemological forms* (e.g., stories, statements, pictures); *epistemological activities* (e.g. gathering information, guessing, brainstorming); and *epistemological stances* (e.g., doubt, making sense or puzzlement, acceptance). Like p-prims, these epistemological resources may be activated in different contexts. However, they are rarely activated in isolation but in networks due to mutual cuing. More recently, Elby and Hammer (2010, p. 1) put forward the idea of an “*epistemological frame*” – “a locally coherent activation of a network of resources that may look like a stable belief or theory” that can be more or less productive in a particular situation. Therefore, teachers should guide students toward more productive framing (e.g., redirect students to work on a problem by focusing on “what they know,” thus shifting them from a “memorizing” to a “sense-making” frame). New frames may “emerge” by activating resources in different combinations. However, future work needs to examine how new resources may develop and change over time, including those needed for more advanced knowledge construction in science (such as the construction of coordination classes and complex scientific models). Some work on learning progressions (discussed below) does begin to address some of these issues. But more work is certainly needed.

The research just reviewed has begun to examine the separate influences of ontological classification and epistemological beliefs on conceptual change, but in more systemic terms than in Phase Two research. Recently, cognitive science research on young children and adults has begun to explore *connections* between both types of influences. Keil and colleagues (Keil, 2011; Keil, Stein, Webb, Billings, and Rozenblit, 2008) have shown that both children and adults are often ignorant of mechanistic details, but have knowledge of higher level functional patterns and principles ("modes of construal") that allow them to know what kinds of properties are likely to be causal or important for entities in different domains. For example, artifacts but not living things are likely to have a purpose (although *parts* of living things may have a purpose); color may be important for distinguishing different living things more than artifacts, while shape may be particularly important for artifacts (given reliance on function.) This kind of knowledge may have ontological import, contributing to picking out different domains. Moreover, in the case of natural kind concepts children and adults adopt an essentialist stance, in which they assume an underlying essence that causally accounts for observed characteristics without knowing the specifics of these causes. Thus, the representation of some concepts may be inherently connected to broad modes of construal and an epistemic stance in which an underlying causal essence is assumed by the learner.

These connections between early concept development and ontological and epistemological beliefs have also been related to the role of other people in the concept learning process. Knowledge of modes of construal may support patterns of deference in a cognitive division of labor in which children as young as four are able to match experts with the appropriate domains of knowledge (Lutz & Keil, 2003), although still in very fragile ways. Moreover, the essentialist stance associated with natural kind concepts has been proposed as the basis for why lay people defer to experts for more detailed accounts and the identification of instances of a concept that they do not know themselves (Carey, 2009).

There are interesting pedagogical implications of these connections among concept learning, ontological and epistemological beliefs and the contribution of other people to individual learning. First, rather than overloading students with too many factual details, curricula should target the development of higher-level forms of knowledge that might offer needed guidance. Recent work has suggested that just such a strategy may be productive. In her cognitive analysis of the types of knowledge undergraduate students use in reasoning about familiar and novel problems about how genes cause diseases or other phenotypes, Duncan (2007) found that students frequently activated *domain general solution frames*. These frames contained placeholders (e.g., something causes *damage* which leads to a *counter-reaction*) that activated *domain specific heuristics* (e.g., genes codes for proteins) that constrained their search for more domain specific solutions (e.g., find the altered protein responsible for this disease). Duncan has built on these analyses (Duncan, Rogat, & Yarden, 2009) to identify important "big ideas" that should be targets for instruction in a learning progression for genetics.

Second, in earlier work on students' epistemological understandings in science, sources of knowledge were often treated as one-dimensional with reliance on *authority* at the unsophisticated end of the pole and reliance on *reasoning, inference*, based on *first-hand experimental* observation, at the other end. As Chinn, Buckland, and Samarapungavan (2011) argue in their recent review on epistemic cognition, there is increasing recognition of the importance of multiple sources (e.g. perception, introspection, memory, reasoning, testimony) that are simultaneously operative and interactive in the sophisticated learner. This type of interaction was examined by Magnusson and Palincsar (2005). In their instruction, they introduce a "second-hand investigation" text (a fictitious notebook of a scientist reporting findings of her studies) as a powerful way of helping students extend their first-hand investigations. They argue that students' initial investigations "prepare" them for engaging with this text meaningfully, while at the same time the text pushes students' investigations forward in new directions. Thus, rather than seeing learning from others and by oneself as antithetical, they are seen as synergistic and mutually supportive. Similarly, Lehrer, Schauble, & Lucas, (2008) have shown that through extended modeling instruction that includes weekly research meetings to provide a carefully designed structure for social interaction in the classroom over the course of the year, sixth grade students developed substantial epistemological sophistication and understanding of the nature of science.

The challenges of designing instruction from more systemic perspectives

The four specific themes that have emerged recently in thinking about the systemic nature of concepts and conceptual change provide more *guidance* for designing effective instruction than the simple dictum 'pay attention to', 'engage', or 'confront' students' prior ideas. They also deepen our understanding of what it means for both student and scientist to have a *complex conceptual ecology*, a central idea introduced in Phase One. In this section, we consider the productive insights of three newer curriculum design frameworks: knowledge integration, learning goals, and learning progressions frameworks. The learning progressions framework builds on many features of the other two and offers a way of thinking about how large-scale transformations in an individual's knowledge and capacity to participate in scientific practices can be brought about that is quite different from Piaget's original developmental vision and has the potential to transform how we design and organize science standards.

Knowledge Integration: Providing sufficient time and guidance to connect, differentiate, and re-organize multiple elements. If conceptual change involves coordinating changes among multiple elements in a complex knowledge network, then it follows that conceptual change will be a slow process because it takes time to add, distinguish, connect, and sort out productive from unproductive connections of these elements across multiple contexts. Linn and her colleagues provided dramatic support for this assumption in an extensive series of design studies of an 8th grade curriculum addressing four key topics in thermodynamics (Clark, 2006; Clark & Linn, 2003; Linn, 2008; Linn & Hsi, 2000).

According to the proponents of the knowledge integration framework, students needed to integrate a variety of different kinds of elements (e.g., nominal and committed facts, p-prims, mental models, narratives, visualizations). Their curriculum focused on developing "intermediate" models, such as a heat flow model, rather than atomic-molecular models. Students integrated knowledge by comparing and contrasting different situations, considering pivotal cases, looking for generalizations, making explanatory connections across topics and between principles and everyday contexts, and re-explaining “disruptive sensory experiences” in terms of more normative ideas.

They found that their full 13-week curriculum was much more effective than three more stream-lined versions (10, 8, and 6 weeks) on measures calling for students to explain and articulate their reasoning across all topics (Clark & Linn, 2003). Follow-up interviews when the students were in 10th and 12th grade, showed that they had not only maintained their understanding, but continued to improve. Overall, they argued that knowledge integration takes more time, but provides a stronger basis for transfer and continued learning. Unfortunately, the typical US 8th grade curriculum allots only 1-2 weeks to thermodynamics, too little time for any serious knowledge integration to occur.

Clark’s (2006) case studies of individuals in the longitudinal sample provide detailed depictions of how the linkages among different ideas were changing during the 13-week curriculum and beyond show that individual restructuring is a “messy” process. For example, Clark found that although adding ideas was easy, normatively connecting ideas was much harder. Students often invented non-normative connections and held multiple contradictory ideas. Students took different paths as they traversed the curriculum – varying not only in rate of progress and ultimate success, but also in which idea was the first they understood, and which gave them the most difficulty. This finding highlights the need for the curriculum to support multiple paths and to devise methods to respond differentially to the needs of students.

Learning Goals Design: Identifying goals by unpacking standards and integrating content and practice in diverse “learning performances.” As researchers investigated how to produce the *deep interest and engagement* that would make conceptual change possible, many began to consider the role that innovative *project based pedagogy* might play in the process. Project-based pedagogy creates a meaningful context for learning (e.g., a driving question about a real-world problem – for example, “How can I make new stuff out of old stuff?”) that students collectively work to solve, with new information and ideas introduced on a “need to know” basis. Thus, learning science content is embedded in investigations that involve students in complex knowledge-building practices (e.g., argumentation, explanation, and modeling) as part of knowledge-building communities.

Building on prior successful work implementing individual project-based units among at risk urban youth (Geier et al., 2008; Marx et al., 2004), Krajcik, Reiser, and colleagues took on the challenge of designing a 3-year middle school project-based science curriculum (IQWST) that was integrated and coherent. To create better alignment among standards, curricular units, and assessments, they developed a Learning Goals design framework (Krajcik, MacNeill, & Reiser, 2008; Nordine, Krajcik, & Fortus, 2011). "Identifying and unpacking" a coherent cluster of standards ("big ideas") that would be investigated in depth in the unit was the first step. Unpacking was needed to identify the component ideas implicit but not fully stated in the standards (e.g., definitions of key terms, relevant background knowledge). Developing "learning performances" for each standard was the second step. A critical assumption was that scientific knowledge was not just a collection of declarative statements and skills, but "knowledge in use" as part of a "knowledge building practice" (p. 7). Hence, for each main idea in the standard, they identified a set of learning performances by combining that idea with important practices (e.g., defining terms, creating models or explanations, designing investigations, making arguments based on evidence). This aspect of their design framework became very influential in later learning progressions work.

The elaborated maps of learning goals and performance then guided the curriculum development phase and were refined through feedback from classroom trials. By the third trial for each unit, they were obtaining gain scores with large effect sizes on all their measures. Further, the recent National Field trials of the IQWST 3-year chemistry curriculum sequence provided evidence that students not only made significant progress across each unit, but also were cumulatively benefiting (i.e., those who had multiple years, did better on subsequent pretests and made larger improvements than those who did not) (Krajcik et al, 2011). Thus, IQWST provided evidence of the benefits of curricular depth and coherence, and responded to the concern raised by prior researchers about the poor alignment across learning goals, curricular activities and assessments of typical middle school curricula (Kesidou & Roseman, 2002).

One reason that IQWST may have been so successful is that, like Linn's heat/temperature unit, it provided the instructional time and depth of focus to allow students to make *connections* among multiple elements in their knowledge networks, and to sort out and revise those connections. It also paid attention to the *language* used in instruction, carefully introducing and discussing with students the meaning of new terms. With a focus on modeling, the curriculum encouraged students to make connections across *different levels of analysis* (e.g., macroscopic vs. nanonscopic) and to see how the same model could explain diverse phenomena. Finally, by being organized around coherent learning goals, it focused on the kinds of "sparse knowledge" (e.g., organizing models and general principles) that may be most helpful in preparing students for further learning. It went beyond Linn's work in investigating how curricular units can build on one another to allow knowledge to become more sophisticated over time (e.g., introducing particulate models in grade 6 to explain the material nature of gas and phase change, developing more elaborated atomic-molecular models in grade 7 to understand and explain simple chemical reactions, etc.)

Learning Progressions: Identifying productive intermediate stepping stones that bridge lower and upper anchors. Learning progressions (LPs) have been described as *testable hypotheses* about (relatively efficient, productive, and complete) paths[2] by which students can be led from their initial ideas and forms of reasoning (*lower anchor*) to a deeper understanding of important theories and concepts in modern science (*upper anchor*). They focus on "big ideas" (often of a disciplinary nature) that take *extended time* to develop and that will not "naturally" develop from interaction with the adult culture without explicit *instructional support*. Because the "conceptual" distance between the lower and upper anchor is so great, the path involves a number of intermediate *stepping stones*, many of which are not yet widely recognized as important by existing standards and curricula. Although the path is continuous, the stepping stones represent important *qualitative* shifts in student understanding. Those successive shifts

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[2] The fact that learning progressions are *models or idealizations* of a relatively strategic pathway is another crucial feature that distinguishes them from the actual *individual learning trajectories* of students (described by Clark, 2006) that are much messier and include dead-ends, and which by their nature are particular events, not generalizations.

are *ordered* not only in terms of increasing complexity (often captured as “levels” in an LP), but also in terms of causal import – that is reaching one stepping stone enables students (makes them more likely) to reach the next (see Corcoran, Mosher, & Rogat, 2009; National Research Council, 2007 for reviews).

Although LPs could be developed for any big idea, including scientific practices such as modeling, most LPs focus on *disciplinary core ideas* (e.g., matter, energy, genetics, evolution, matter and energy flow in living things, celestial motion). Disciplinary core ideas are a meaningful locus for LPs, because they provide a context for integrating the development of scientific epistemology and practices with the development of specific content understanding.

In keeping with the systemic turn for analyzing concepts and conceptual change, both the lower and upper anchors and the evolving knowledge network the LPs describes, have increasingly been analyzed in terms of multiple components. For example, new work in developmental psychology identifies multiple types of early knowledge elements that can be used as resources for science learning. These include some initial concepts for a given domain (e.g., object, material, weight, and size, for matter; diverse types of living things, individual differences, growth and change, places where organisms live, for evolution), a wide range of image-schemas possibly assembled in models, ontological assumptions (e.g., weight is heft, species are kinds), and epistemological commitments (e.g., senses are a reliable source of information; there are hidden essences) that mutually support each other. Even preschoolers are aware of multiple forms of explanation across domains (e.g., contact causality, intentional causality; causal explanations in terms of needs or purpose; explanations by analysis into parts), and are also developing mathematical competence, symbolic competence, metacognitive abilities and epistemic understandings. What is a relevant part of the lower anchor for a given LP is not a tightly organized initial theory, but rather all the elements that will be drawn on in developing further knowledge for that LP; some are already used and partially inter-related to understand the domain, but many others are yet to be related to that domain, or are only of peripheral importance. (See National Research Council, 2007, chapters 3, 5, and 6, for reviews of these foundational resources.)

The upper anchor is often characterized as a “framework of understanding” that includes multiple interrelated concepts and models, forms of symbolization, and supporting ontological and epistemological assumptions. For example, understanding atomic-molecular theory (AMT) not only involves understanding the core tenets of the theory, but also how different models explain a variety of macroscopic phenomena (e.g., transmission of smell, phase change only require a particulate model, while chemical reactions require an atomic-molecular model). Such understandings rely on interpretations of matter and its behavior at the macroscopic level (e.g., material, phase change, weight, volume, density, mass) that are scientifically compatible with AMT. It also involves making an ontological distinction between atoms and molecules, understanding the nature and function of models, and having an epistemology that includes emergent properties, in order to grasp that atoms, invisible to the naked eye can form visible matter with physical and perceptual properties they themselves do not have (Wiser & Smith, 2013). Characterizing both the upper and lower anchor, in terms of multiple related elements, contrasts with the much narrower focus of earlier conceptual change work, which focused on one or two concepts, a domain at a time.

Thinking about the upper and lower anchor as a complex knowledge network raises the challenge of how to describe what progresses in terms of productive stepping stones and achievable conceptual changes. A recent synthetic report by a large group of LP researchers concluded:

> ….the most compelling way to characterize the successive levels of understandings we think students will proceed through if they are to reach the goals for high school science, is to frame them as a series of successively more sophisticated explanatory models that take into account more and more of the relevant phenomena and that move from naive explanations based on folk concepts and directly observable interactions to models that deal with hypothesized interactions among constructs and entities that are observed or measured only with sophisticated tools and/or inferred from their observed effects. (Rogat et al., 2011, pp. 4-5).

An advantage of organizing these stepping stones around *models* is that models integrate multiple knowledge elements (e.g., image schemas, propositional beliefs) as well as embody different ontological and epistemological commitments.

The number of intermediate models that have been recognized in recent LP work is striking because many are entirely overlooked by current standards and instruction. These break the distance between the upper and lower anchor into several more manageable steps, making it more likely to move students' knowledge networks forward while maintaining coherence. For example, at least 5 different intermediate models have been proposed within a K-12 matter LP—a macroscopic compositional model, a microscopic compositional model, a particle model, an atomic-molecular model, and a sub-atomic model based on the Bohr model. The first two are crucial in elementary school, and the last three in middle and high school (Rogat et al., 2011). Similarly, Lehrer and Schauble (2012) have proposed a sequence of four increasingly complex ways elementary students can model variation, change, and ecosystems to lay a foundation for evolutionary thinking. They emphasize gradually "expanding the repertoire of student models" for variation and change through introducing *new representational means* such as annotated drawings, tables of measures, frequency displays of distribution, chance models of distribution, thus also highlighting the powerful role that student generated *external representations* can play in helping students "get a grip" on nature and in developing student understanding of the epistemic practice of modeling.

Research results from specific LP projects are just beginning to be reported and it will, of course, take some time to develop, revise and test conjectures about productive stepping stones in different domains, as well as to assess the overall value of the LP approach. But already one result is clear: elementary school children are capable of developing much more sophisticated models and understandings than is observed with traditional instruction (see Doubler et al., 2011, for matter; Lehrer & Schauble, 2012, for concepts laying the foundation for evolutionary thinking). An exciting next step will be not only to continue to clarify our understanding of knowledge growth in the elementary school years, but also to explore how learning in the middle and high school years is affected by this foundational preparation, as well as what the long term payoffs might be.

Conclusion

We have organized our review of the literature on student conceptions and conceptual change in terms of three overlapping phases of research that we believe capture broadly the progress that has been made in the field since the rejection of Piaget's stage view of development. His domain general view of conceptual development in terms of changes in logico-mathematical structures has now been replaced by a systemic view of concepts and conceptual change involving complex interactions between various forms of knowledge: propositionally expressed beliefs of various kinds (domain specific, ontological, and epistemological) and iconic representations that help ground understanding in perception and action (image-schemas, imagery and mental models). These knowledge elements are distributed across internal and external representations, and processes of change involve processes internal to individual learners' minds and interactions with others (including more knowledgeable individuals and peers). Future research will need to take on the challenge of improving our understanding of this complexity and fostering conceptual change through instruction that takes this understanding into account.

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