A History of Conceptual Change Research: Threads and Fault Lines

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Characterizing Conceptual Change

For the learning sciences, conceptual change is best defined by its relevance to instruction. Some topics seem systematically extremely difficult for students, and conventional methods of teaching usually fail. Topics at all age levels are affected, including, in physics: matter and density, Newtonian mechanics, electricity, and relativity; in biology: evolution and genetics.[1] Conceptual change contrasts with less problematic learning, such as skill acquisition (learning a physical skill or an algorithm for long division) and acquisition of facts (such as “basic number facts” for addition or multiplication). If there are difficulties in these areas, they are for more apparent reasons such as sheer mass of learning or the necessity of practice to produce quick, error free performance.

The name “conceptual change” embodies a first approximation of the primary difficulty: students must build new ideas in the context of old ones, hence the emphasis on “change” rather than on simple accumulation or (*tabula rasa*, or “blank slate”) acquisition. Strong evidence exists that prior ideas constrain learning in many areas. The “conceptual” part of the conceptual change label must be treated less literally. Various theories locate the difficulty in such entities as “beliefs,” “theories,” or “ontologies,” in addition to “concepts.”

Conceptual change is among the most central areas in the learning sciences for several reasons. First, many critically important ideas in science are affected by the challenges of problematic learning. Conceptual change also engages some of the deepest theoretical issues concerning learning. What is knowledge? When and why is it difficult to acquire? What is deep understanding; how can it be fostered? Conceptual change is important not only to education but also to developmental psychology, epistemology, and the history and philosophy of science. For example, how did Newton, Copernicus, and Darwin accomplish what they did?

Conceptual change research is difficult to review. Problems (what changes; why is change difficult; how does it happen?) have led only slowly to solutions, and solutions have been tentative and partial. Many academic disciplines have examined conceptual change, resulting in a wide range of perspectives that can be hard to reconcile. There are no widely accepted, well-articulated and tested theories. Instead, the field consists of multiple perspectives that combine many commonsense and theoretical ideas in kaleidoscopic fashion. In this chapter I highlight

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[1] The conceptual change paradigm is less often applied to other areas of science, and much less in mathematics.

critical *threads* and *fault lines*—the former through a historical orientation and the latter by noting a few important changes in perspective and differences of opinion.

Preview

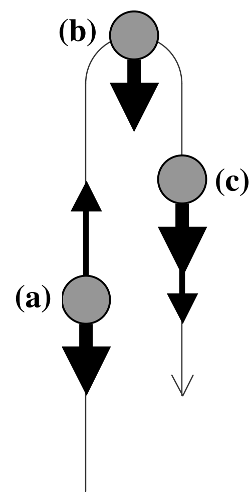

Figure 1. Expert (one force) explanation of a toss: (a) Gravity (thick arrow) drives the ball's velocity (thin arrow) downward, (b) bringing it to zero at the peak, (c) then gravity extends velocity downward in the fall.

The concept of force provides an excellent example of conceptual change. Figure 1 shows an expert's conceptualization of a simple event, tossing a ball into the air. Physicists maintain that there is only one force, gravity (thick arrow in the figure), on the ball after it has left the hand. Gravity acts on the speed of the ball (thin arrow), diminishing it until the object reaches zero speed at the peak of the toss. Then, gravity continues to "pull" the speed of the ball downward, accelerating the ball downward.

Before conceptual change research, instructors would have attributed student difficulties with the toss to the abstractness of physics, or to its complexity. Instructional interventions might include re-organizing or simplifying exposition. "Say it better" is a "blank slate" reaction to student difficulties. In contrast, listening closely to student explanations yielded a stunning discovery. Students do not just lack knowledge; they think differently than experts. Figure 2 illustrates a widespread, cogent-sounding novice explanation, involving two forces. Your hand imparts a force that overcomes gravity and drives the ball upward. The upward force gradually dies away until it balances gravity at the peak. Then, gravity takes over and pulls the ball downward.

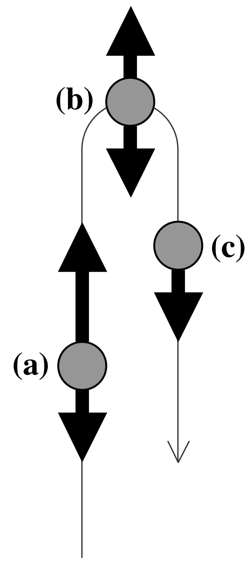

Figure 2. Novice (two force) explanation of a toss: (a) An upward force, imparted by the hand, overcomes gravity and drives the ball upward, (b) but the imparted force gradually dies away and comes into balance with gravity, (c) finally, the imparted force is overcome by gravity.

The two-force explanation illustrates that students have a prior concept of force and what forces do, different from experts. Instruction must deal with prior ideas and change them: enter conceptual change.

How should one deal with students' "misconceptions," such as this one? Early on, most assumed that student ideas were coherent, like a physicist's. Then, one has little choice but to argue students out of their prior ideas, convincing them to accept the scientifically correct conceptualization. But a very different view has gradually developed. Rather than a coherent whole, students' ideas consist of many quasi-independent elements. Instead of rejecting student conceptions altogether, one can pick and choose the most productive ideas, and refine them to create normative concepts. For example, students see balancing at the peak of the toss. But, balancing is a rough version of an incredibly important principle in physics, conservation of energy. Similarly, the upward "force" in the incorrect explanation is not absent, but it is what physicists call momentum.

The opposing views of students' naïve ideas as either (1) coherent and strongly integrated or (2) fragmented constitute a watershed fault line in the history of conceptual change. That fault line will permeate this chapter, as it has permeated the history of conceptual change research.

I turn to a chronology of conceptual change research.

Premonitions in the Work of Piaget

Jean Piaget contributed an immense body of work on children's understanding (Gruber & Voneche, 1977). He found that children think quite differently than adults. This discovery had a strong influence on the foundations of conceptual change. Piaget introduced the idea of *genetic epistemology*—the study of the slow growth of knowledge and intelligence—which contrasted with philosophers' (e.g., Plato, Descartes, Kant) prior emphasis on timelessness and certainty. His empirical work touched many domains, including biology (the concept of "alive"), physics ("force"), space and time (perspective and simultaneity), representation (drawing), categorization, and logic. His biological work has been particularly influential on conceptual change research.

Piaget established the core idea of *constructivism*: new ideas always emerge from old ones. Indeed, this orientation seeded conceptual change, itself. Constructivism and the astounding revelation that children systematically think quite differently than adults constitute the most important threads from Piagetian studies into conceptual change.

Some other of Piaget's methodologies and theory also penetrated conceptual change. For example, Piaget introduced the idea of clinical interviews as a way of investigating children's thinking. His grand epistemological program sought to find similarities, if not identical principles of development, between children's developing ideas and the history of science. Other elements of his thinking—the idea of disequilibration and re-equilibration as a mechanism of change, assimilation versus accommodation, reflective abstraction, and others—were important mainly at early stages of conceptual change research.

A definitive fault line into modern conceptual change research was that Piaget developed a domain-independent "stage theory" of intelligence, where concepts in every domain reflect the same global changes in thinking. Conceptual change is a domain-specific approach; each domain follows its own sequence of conceptions.

The Influence of the Philosophy and History of Science

To many, Thomas Kuhn defines the enduring relevance of the history of science to conceptual change. Kuhn, however, had strong opposition within the history of science. In particular, Stephen Toulmin anticipated important opposition to Kuhn's ideas. The enduring fault line between coherence and fragmentation, which I introduced in the Preview section, can be traced back to Kuhn (coherence) vs. Toulmin (fragmentation).

Kuhn's Scientific Revolutions

In his landmark work, *The Structure of Scientific Revolutions* (1970), Kuhn broke from his predecessors in his view of progress in science. Kuhn rejected the idea that science progresses incrementally. Instead, he claimed that ordinary "puzzle solving" periods of science, called *Normal Science*, are punctuated by revolutions, periods of radical change that work completely differently than Normal Science. In particular, the entire *disciplinary matrix* (referred to ambiguously but famously as a "paradigm" in the earliest edition) gets shifted in a revolution. What counts as a sensible problem, how proposed solutions are judged, what methods are reliable, and so on, all change at once in a revolution. Kuhn famously compared scientific revolutions to gestalt switches (consider Jastrow's duck-rabbit, Necker cubes, etc.), where practitioners of the "old paradigm" and those of the "new paradigm" simply do not see the same things in the world. Gestalt switches happen when the coherence of ideas forces many things to change at once.

Kuhn articulated his belief in scientific revolutions in terms of *incommensurability*. Incommensurability means that claims of the new theory cannot be stated in the terms of the old theory, and vice versa. Incommensurability constitutes both a definitional property of conceptual revolutions and also an explanation for their problematic nature. As such, Kuhn's incommensurability established an enduring thread in conceptual change work. In contrast, sociological aspects of Kuhn's views were not imported into conceptual change work:

> Scientific knowledge, like language, is intrinsically the common property of a group, or else nothing at all. To understand it we shall need to know the special characteristics of the groups that create and use it. (p. 208)

Toulmin's Rejection of Strong Coherence

The main thrust of early conceptual change followed Kuhn, and it ignored competing perspectives. Stephen Toulmin's *Human Understanding* (1972) appeared only a few years after The Structure of *Scientific Revolutions,* and this work perspicuously introduces the other side of the coherence vs. fragmentation fault line.

Human Understanding begins with an extensive review and rejection of assumptions about the level and kind of coherence (Toulmin used "systematicity") that philosophers assumed in scientific thought. Toulmin traces the "cult of systematicity" back to the model of logico-mathematical coherence taken from certain mathematical forms, such as an axiomatic view of Euclidean geometry.[2]

Presumptions of coherence were, for Toulmin, pernicious. Not only is there no global framework for all science (as claimed by the philosopher Kant), but the assumption that particular theories are strongly coherent fails also. Toulmin directly criticizes Kuhn. Incommensurability appears only when one makes the mistake of assuming strong coherence. Furthermore, incommensurability also guarantees that change will always appear mysterious—everything changes at once (Kuhn's "gestalt switch").

> Rather than treating the content of a natural science as a tight and coherent logical system, we shall therefore have to consider it as a conceptual aggregate, or 'population', with which there are—at most—localized pockets of logical systematicity. (p. 128)

In the context of his attack on coherence, Toulmin made an important methodological observation. He maintained that the dominant "before and after" (revolutionary) view of conceptual change had to be abandoned.

> This change of approach [away from strong coherence] obliges us to abandon all those static, 'snapshot' analyses…. Instead, we must give a more historical, 'moving picture' account…. (p. 85)

This parallels a gradual shift from before-and-after studies of conceptual change to process-based accounts.

Misconceptions

> *Even the brightest students in the class [have] false ideas based on enduring misconceptions that traditional instructional methods cannot overcome.*
> Promo materials for A Private Universe: Harvard-Smithsonian Center for Astrophysics (1987), http://www.learner.org/onesheet/series28.html

Starting in the mid 1970s, a huge social movement, which we dub "misconceptions," began modern conceptual change studies in education and in developmental and experimental psychology. The movement exploded to prominence in the early 1980s, spawned a huge

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2 Toulmin does not restrict his critique to strictly logical forms of systematicity. For example, he also rejects Collingwood's model of "systematicity in hierarchical presumptions," which will be relevant in later discussion.

literature, and tailed off somewhat in the early 1990s, although its influence is still strong. The strength of the movement can be gauged by the fact that an early bibliography collected literally hundreds of studies (Pfundt & Duit, 1988). Confrey (1990) provided an excellent review of misconceptions in physics, biology, and mathematics.

Three European women were important contributors. R. Driver, L. Viennot, and A. Tiberghien did foundational studies, often involving instructional interventions, of topics like elementary school students' conceptions of matter, middle school heat and temperature, and high school force and motion (Driver, 1989; Tiberghien, 1980; Viennot, 1979). These and other researchers discovered, documented, and theoretically considered "false beliefs" such as: "tiny specks of matter don't weigh anything," "an object's speed is proportional to the force on it" (Newton found that force controls *acceleration*, not velocity), and "heat and cold are different things."

In the U.S., some important early misconceptions researchers were D. Hawkins (1978), J. Clement (1982), J. Minstrell (1982), and M. McCloskey (1983a & b). Hawkins described the presence of false ideas that systematically block science learning as "critical barriers." Others used different terms for the same idea, such as alternative conceptions, alternative frameworks, intuitive or naïve theories, and naïve beliefs. The term "misconceptions" was most used.

A positive influence of misconceptions studies was bringing the importance of educational research into practical instructional circles. Teachers saw vivid examples of students responding to apparently simple conceptual questions in incorrect ways. Poor performance in response to basic questions, often years into instruction, could not be dismissed. Apparently, students had entrenched, "deeply held," but false prior ideas. The obvious solution was usually phrased in terms of "overcoming" misconceptions, convincing students to abandon prior ideas.

This simple story—entrenched but false prior beliefs interfere with learning and need to be overcome—was compelling to educators, and resulted in significant funding and publicity. Many leading researchers would go on to develop more refined views, some elements of which are reviewed below. However, public impact and most research remained largely at the primitive level of documenting misconceptions, rather than approaching deeper questions, such as: What is a concept? Can we decompose concepts into pieces, or are they unitary? Do multiple concepts fit into coherent wholes? If so, how coherent is the whole? Most important for the learning sciences, how do we see genuine scientific concepts developing out of naïve ones?

Three Early Threads

The analogy with the history of science

Three important and related threads in conceptual change research came to prominence simultaneously early in the misconceptions movement. Arguably the most influential was the analogy of the development of students' ideas with the history of science, which we marked in Piaget's work. Susan Carey (1991, 1999) was one of the most consistent in drawing on Kuhn's ideas about scientific change in the context of children's conceptual change. She has systematically used the idea of incommensurability as a primary earmark of conceptual change. Incommensurability distinguishes conceptual change from "enrichment" (adding new ideas or beliefs) or even mere change of beliefs. Carey's main work was in biology, where she argued that children undergo a spontaneous and important conceptual revolution (Carey, 1985). For example, the concepts "alive," "real," and "intentional" (meaning having psychological wishes and desires) are confused in children's minds before they sort out a true biology, wherein "alive" means precisely that the bodily machine continues to work, sustaining life. Carey was influenced by Piaget but argued that domain-independent theories of intelligence cannot explain changes in childhood biology. Carey's extensive empirical and theoretical argumentation constituted an influential landmark, especially among developmental psychologists.

Carey worked with Marianne Wiser in the domain of heat and temperature, where a prominent sub-thread of the analogy with the history of science appeared. Not only are the *forms* (structures and processes, such as concepts, theories, incommensurability, and radical restructuring) similar in children's conceptual change and in the history of science, but *content,* itself, shows remarkable commonalities as well. Wiser and Carey (1983) built the case that naïve conceptions of heat and temperature parallel the ideas of an early group of scientists.

The analogy with history of science has been used in multiple ways. Karmiloff-Smith (1988) denied or downplayed content parallelism between child development and the history of science, but she highlighted process-of-change parallelisms. Nercessian (1992) advocated the use of "cognitive-historical analysis" empirically to determine the processes scientists' use in changing theories. Those processes include using analogical and imagistic models to bootstrap from simpler to more advanced theories, thought experiments, and extreme cases. Nercessian suggested that educators should encourage use of the same processes in order help foster students' conceptual change in school (p. 40).

The theory theory

The theory theory is the claim that children or beginning students have theories in very much the same sense that scientists do. Carey has consistently advocated a version of the theory theory. With respect to "theories of mind," Allison Gopnik (Gopnik & Wellman, 1994) advocates very strong parallels between children and scientists. Others are more conservative in supporting weaker parallels (Vosniadou, 2002). Theory theorists generally align themselves with the coherence side of the coherence/fragmentation fault line.

Michael McCloskey (1983a, b) performed a series of studies that became perhaps the most famous of all misconceptions studies. He claimed that students entered physics with a remarkably coherent and articulate theory (suggested in Figure 2) that competed directly with Newtonian physics in instruction. McCloskey's theory theory included a strong parallel in content to medieval scientists' ideas, such as those of John Buridan and Galileo. In contrast to others, however, he made little of process-of-change similarities and, for example, did not refer in any depth to Kuhn or the philosophy of science. He took content parallels to ideas in the history of science as empirical facts, unrelated to theories of change.

McCloskey's work was incredibly influential. Despite empirical and theoretical claims by others, McCloskey has often been cited authoritatively as showing that naïve ideas in physics are strongly coherent, and, indeed, theoretical in the same way that scientific theories are (e.g., Wellman & Gelman, 1992, p. 347).

A rational view of conceptual change

Introducing rational models of conceptual change marked another early landmark. Rational models hold that students, like scientists, maintain current ideas unless there are good reasons to abandon them. Posner, Strike, Hewson, and Gertzog (1982) established the first and best-known rational model. They argued that students and scientists change their conceptual systems only when several conditions are met: (1) they become *dissatisfied* with their prior conceptions (experience a "sea of anomalies" in Kuhn's terms); (2) the new conception is *intelligible*; (3) beyond intelligible, the new conception is *plausible*; (4) the new conception appears *fruitful* for future pursuits (in Lakatos's, 1970, terms: should offer a *progressing paradigm*).

Posner et al.'s framework was eclectic. It drew from both Kuhn and Lakatos, despite Lakatos's criticism of Kuhn as viewing science as "mob rule." The framework drew equally from Kuhn's opponent, Toulmin, appropriating the idea of "conceptual ecology." A later version of this framework (Strike & Posner, 1990) retreated from a purely rational framework, admitting such factors as motivation and non-verbal forms of knowledge.

Posner et al. maintained that their framework was epistemological and did not reflect psychological reality or provide a model for instruction. Still, many science educators organized instruction around the framework (e.g., Smith, Maclin, Grosslight, & Davis, 1997). Some even introduced students explicitly to the framework (Hewson & Hennessey, 1992).

Assessing the Misconceptions Movement

Positive contributions:

1. Misconceptions highlighted qualitative understanding and explanation against a historical background that emphasized only quantitative problem solving.
2. Misconceptions established visibility for constructivist thinking, in contrast to "blank slate" models of learning.
3. Misconceptions provided foci for instructional problems and new measures of learning. It diminished attention to domain-general difficulties (e.g., Piagetian stages) and emphasized domain-specific issues.

Negative contributions:

1. Most misconceptions studies were relatively devoid of theory. The "depth" of misconceptions was often uncalibrated, and the meaning of "concept" or "theory" remained unexamined.
2. Misconceptions work exclusively emphasized negative contributions of prior knowledge.
3. How learning is actually possible was minimally discussed.
4. Misconceptions led to a preemptive dominance for theory theory points of view and "conflict" models of instruction (Posner et al.'s framework; McCloskey, 1983a; Hewson & Hewson, 1983).

Smith, diSessa, and Roschelle (1993) provide an analysis of the misconceptions movement.

Beyond Misconceptions

Conceptual Change in Particular Domains

What, in detail, do students or children know about any particular domain at any particular age? Since Piaget, this has been an important question. However, modern conceptual change research is asking this question with greater precision and empirical support, in more instructionally relevant domains, than previously.

In the domain of biology,[3] a substantial community of researchers (Carey, Keil, Hatano, Inagaki, Atran, and others) shared innovative methods, critiqued, and built on each other's ideas. Carey (1985, 1986) argued that a domain specific conceptual change—which involves "radical

[3] Naïve psychology and naïve physics were other notable domains of study. Coverage was most spotty in physics. Studies of baby cognition revealed stunning early physics competence (Spelke, Philips, & Woodword, 1995; Baillargeon, 1986). But, middle years received less attention. Late development was left to misconceptionists.

restructuring" rather than a mere "accretion of ideas"—occurs in childhood. She maintained that the early concept of "animal" was embedded in a naive theory of psychology; animals are distinct from inanimate objects in their goal-directed (psychological) activities. In contrast, biologists attend to animals' structure and internal processes, the "bodily machine" of which young children are nearly completely ignorant. She claimed that a true biology appears only by about age 10.

The burgeoning field of children's biology revised and refined Carey's ideas, leading to a wonderfully enriched view of the emergence of biological knowledge. Two prime innovators were Frank Keil and Giyoo Hatano (with his collaborator, Kayoko Inagaki). These researchers pushed the emergence of distinctively biological thinking back about six years. Keil developed an extensive program that isolated children's sensitivity to biological phenomena in multiple strands, including the biological essence of animals, inheritance, biological contagion, and the distinctive properties of the "insides" of living things. In the latter category, Keil (1994) showed that children age 4 or earlier expect the insides of rocks to be random while plants and animals have more organized insides. Keil showed that very young children believe it is easy to paint or in other ways physically change a skunk into a raccoon, while older children, still before the age of 6, feel such operations cannot essentially change the creature. He showed that children come early to the idea that inheritance ("nature") is more important than environment ("nurture") in establishing the essential characteristics of animals.

Inagaki and Hatano (2002) brought a new order to early biology by describing a core naïve theory, a *vitalist* biology. In this theory, the ingestion and use of a "vital force" accounts for animals' activity, health, and growth. Experiments showed that vitalist biology emerged by age 6. Hatano, Inagaki, and Keil argued and empirically disputed Carey's claim that biology emerged from psychology. However, Inagaki and Hatano agreed with Carey that the shift from childhood to mechanistic biology (age 10-12) constituted true conceptual change.

Knowledge in Pieces

The theory theory thread dominated studies of naïve biology, psychology, and physics. It represents the "coherence" (Kuhnian revolutions) side of the coherence/fragmentation fault line. The historical line, "knowledge in pieces," takes the "fragmented" side. Minstrell and diSessa were early advocates of knowledge in pieces. They advanced Toulmin's critique of strong coherence.

Minstrell (1982, 1989) viewed naive ideas as resources for instruction much more than blocks to conceptual change in physics. This directly challenged the misconceptions view that naïve ideas are simply wrong, and it also challenged the theory theory notion that naïve ideas must be taken or rejected as a whole. Minstell described intuitive ideas as *facets*, "threads" that, rather than rejecting, need to be "rewoven" into a different, stronger, and more scientific conceptual fabric. Facet work has charted hundreds of ideas that students have upon entering instruction in many topics (Hunt & Minstrell, 1994). Coherent naive theories are nowhere to be seen.

diSessa (1983) introduced the idea that naïve physics consisted largely of hundreds or thousands of elements called p-prims, similar to Minstrell's facets. P-prims provide people with their sense of which events are natural (when a p-prim applies), which are surprising, and why. P-prims are many, loosely organized, and sometimes highly contextual, categorically unlike "theories." With good instructional design, p-prims can be enlisted—rather than rejected—into excellent learning trajectories. For example, "Ohm's p-prim" prescribes that more effort begets more result, and a greater resistance begets less result. Ohm's p-prim accounts for the easy learnability of Ohm's law in electrical circuit theory, and it can be invoked to help students understand other physics, such as thermal equilibration (diSessa, in press).

Knowledge in pieces was, at best, a minority opinion in early educational studies of conceptual change (Driver, 1989; Smith et al., 1997). It remains largely ignored in developmental psychology. See diSessa, Gillespie, and Esterly (2004) for a historical review. However, the viewpoint has gained visibility and adherents in educational circles. Marcia Linn (this volume), for example, elaborated "scaffolded knowledge integration" as an instructional framework. In this view, the multiplicity of intuitive ideas is explicitly recognized, and integration (increasing coherence) is virtually the definition of conceptual advancement.

Fragments of Theory

I referred earlier to conceptual change research as kaleidoscopic; many threads are combined in diverse ways into many different theoretical perspectives. This section sketches the theoretical landscape of conceptual change in terms of some of those threads.

I discuss two groups of theoretical issues. First, what are the mental entities involved in conceptual change, and how are they organized? Second, why is conceptual change difficult, and how does it happen when it does? The various answers to these questions radically shift how we think about the design of good instruction.

Components and systems in conceptual change

What changes in conceptual change? The obvious answer is "concepts." Shockingly, there is very little agreement in the field on the meaning of the term "concept" and concepts' role in conceptual change.

Carey (1986) distinguished beliefs from concepts. Beliefs are relational entities. For example, "people are animals" relates two concepts, people and animals; Newton's laws ($F = ma$) relate the concepts force, mass, and acceleration. Carey believed that belief change is relatively easy, and that the difficulty is change in the very concepts in which beliefs are expressed. When children finally believe that people are animals, a very different concept of animal is implicated, compared to their earlier conceptions.

In Carey's theory theory perspective, concepts are components of larger-scaled systems, intuitive theories, which strongly constrain concepts. Most theories of conceptual change are *nested* in this way. At least two levels exist (*components* in a *system*), and the relational constraints involved at the system level are critical. Systemic relations constrain individual concepts, and therefore incremental change is difficult. This brings us directly to the core of the coherence vs. fragmentation fault line. If systemic constraints are too strong (that is, if coherence is high), then change is unimaginable, as Toulmin advised. So, a great deal rests precisely on understanding relations at the system level, which is the naïve theory in Carey's case.

Vosniadou proposed two versions of nesting. Concerning children's models of the earth's shape (sphere, pancake, etc.), she implicated *framework theories* at the system level. When children are asked questions about the shape of the earth, their framework theories constrain generation of specific models (at the component level) to a few possibilities. In this case, *models* are nested in, and constrained by, framework theories. Models change relatively easily, but framework theories take a long time. In more recent work, Vosniadou extended her ideas to force and motion. In Ioannides and Vosniadou (2002), framework theories constrain meanings (not models) such as “force,” and the higher, relational level (theories) is still the real locus of difficulty in change.[4]

Another nested view of conceptual change involves concepts as components, but the higher level is not theories, but ontologies (fundamental categories, like matter, processes, or ideas). Micheline Chi (1992) posited that concepts are strongly constrained by their presumed ontology. In early work, Chi maintained that concepts of intuitive physics were nested in the matter ontology, but Newtonian concepts lie in an ontology very different from matter, “constraint-based processes.” Shifting onotologies, like shifting theories, is very difficult. Instructionally, Chi suggested teaching the new ontology first, and then revised concepts can grow naturally within that ontology.

Adherents of the knowledge-in-pieces view feel that classical knowledge terms (concepts, theories, ontologies) are not up to the scientific job of explaining conceptual change; we need new terms. Minstrell introduced “facets.” I introduced a series of constructs, each with its own definition: for example, *p-prims*, *mental models*, and *coordination classes* (diSessa, 1996; diSessa & Wagner, 2005). A coordination class is a model of a certain kind of concept. Coordination classes are complex systems that include many coordinated parts, including p-prims. There is recursive nesting here: P-prims are nested in coordination classes (concepts), and coordination classes—along with mental models and other entities—constitute the “conceptual ecology” of students, which is parallel to but different from “theory.”

The fact that concepts (coordination classes) are explicitly modeled is virtually unique to this view conceptual change[5] and has important consequences for instructional design. Knowing the internal pieces of concepts is much like having an ingredient list for baking a cake. Knowing how those internal pieces are configured is almost like having a recipe.

Models of constraint and change

Following Kuhn, incommensurability has been a proposed difficulty in change. In view of incommensurability, how is conceptual change at all possible? Inspired by the history of science, various researchers proposed mechanisms like analogy and developing imagistic models. A common assumption is that differentiation of diffuse initial concepts (heat and temperature become distinct), and coalescence of old categories (plants and animals become joined in the category of living things) are important processes that take place in overcoming incommensurability (Carey, 1986, 1999; Smith et al., 1997).

A generic difficulty in the knowledge-in-pieces view is merely collecting a large set of elements (say, p-prims) into a system (say, a scientific concept). Unlike baking a cake, one cannot collect conceptual ingredients all from a store. Instead, students need to have diverse experiences in developing a concept. In addition, the conceptual ingredients must be coordinated into a smoothly operating system. Coordination class theory specifies a kind of coherence, called *alignment*, that poses systematic and empirically tractable difficulties for students. The theory also delineates some standard paths to overcoming them.

In cases where there might be no intuitive theory (chemistry?; mathematics?), incommensurability does not exist. Many theories of conceptual change, then, cannot explain learning difficulties. However, collecting and coordinating pieces still applies. So, learning can still be tracked by knowledge in pieces.

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4 Vosniadou often emphasizes the nature of framework theories as “background assumptions,” similar to Collingwood’s view, which Toulmin criticized for lack of rendering such assumptions explicit and testable.

5 Neither Carey, Vosniadou, nor Chi describe the internal structure of concepts.

Rational models continue to be surprisingly well regarded, despite sparse evidence for their adequacy in dealing with conceptual change. Gopnik and Wellman (1994) mention most of the same elements as Posner et al. They also mention quasi-rational processes resonant with professional science, such as denial of the need for change and the formation of auxiliary hypotheses to fend off deep change.

Although Piaget's equilibration has diminished in popularity, some new versions have appeared. Inagaki and Hatano (2002, pp. 173-175) provide two models of conceptual change where new ideas disturb the coherence of prior ideas, and re-establishing coherence drives conceptual change. See also Ioannides and Vosniadou (2002, p. 58).

Instruction

The topic of implications of conceptual change research for instruction is as complex as surveying the field of conceptual change itself. However, here are a series of observations about the knowledge-in-pieces (KiP) perspective and instruction.

1. *KiP allows "watching" conceptual change*: Teachers or tutors organize students' attention over short periods of time. KiP has a small enough grainsize of analysis to allow real-time tracking of learning (diSessa, in press). This means, in particular, that instructional design can use, not just before/after studies, but also process data for formative feedback.
2. *KiP explains why conceptual change takes time*. Every view of conceptual change assumes that it takes a long time. However, KiP proposes its own distinctive reasons, which allows one to monitor and remediate difficulties. One such problem is that creating a coherent concept requires aligning (in the technical sense discussed earlier) multiple distinct ways of using that concept.
3. *KiP requires learning in many contexts*. Complex contextuality is a fact of the matter in a KiP perspective. There is no alternative to exposing students to multiple contexts during learning, so that they may learn in each.
4. *Students have rich conceptual resources on which to draw*. A nearly unique property of KiP in the field of conceptual change is that it sees "naïve" students as full of ideas, many of which can or even must be re-used in developing scientific understanding (diSessa, in press).
5. *Confront and replace is an implausible instructional strategy*. With hundreds of relevant ideas in their conceptual ecology, the idea of separately eliminating all the wrong ones is implausible, even if it were desirable.
6. *Coaching students meta-conceptually is very different from a KiP perspective*. Most contemporary researchers feel that students should learn about their own learning and about the nature of scientific concepts. As Kuhn differed from Toulmin, KiP differs from theory theory views with respect to the nature of both students' and scientists' ideas.
7. *KiP is flexible and fine-grained enough to track individual differences in learning*. "One theory fits all," does not work. The grainsize of KiP analyses allows one to characterize student differences and to see how they influence learning (Kapon & diSessa, 2012)

As much as everyone in conceptual change research wants to improve instruction, modesty is still very important. Evaluating theories of conceptual change *by the success of instruction inspired by them* is not yet, in my view, something to assume.

1. Instruction is a complex mixture of design and theory. Good intuitive design can override the power of current theory to prescribe successful methods. Almost all reported conceptual-change-inspired interventions work; none of them lead to unquestionably superior results.
2. Researchers of different theoretical persuasions advocate similar instructional strategies. Both adherents of knowledge in pieces and of theory theories advocate student discussion, whether to draw out and reweave elements of naïve knowledge, or to make students aware of the faults in their prior theories. The use of instructional analogies, metaphors, and visual models is widespread and not theory-distinctive.
3. Many or most evaluations of interventions, at present, rely primarily on pre/post evaluations, which do little to discern specific processes of conceptual change.

Mapping the Frontier

Coherence: A Central Fault Line

Thomas Kuhn had a huge influence in the early days of conceptual change with the idea that scientific theories change drastically and holistically. He should likely be credited with seeding the theory theory, that conceptual change replaces one coherent theory with another, and the sticking point is precisely the coherence of the prior theory. Coherence is a byword for theory theorists, and it is taken to be the defining attribute that makes the term "theory" applicable to naïve ideas (Wellman & Gelman, 1992). However, Toulmin's critique of Kuhn—that scientific understanding is not strongly coherent—has proved prescient. Almost no models of coherence exist,[6] and data for coherence has been ambiguous and contested. There is increasing evidence that the knowledge-in-pieces perspective provides a more apt framework for instructional difficulties and possibilities concerning conceptual change, even thought the issue of coherence is ignored by some influential researchers, and dismissed as unimportant by others (Chi, 1992, p. 161).

Recent studies have explicitly provided empirical and theoretical argument and counter-argument concerning coherence in naïve ideas (Ioannides & Vosniadou, 2002; diSessa et al., 2004; Hammer & Elby, 2002). The ascendancy of views favoring fragmentation seems vivid in education. For example, Minstrell's facet analysis has been extensively developed and brought to widespread instructional practice; I am unaware of instruction based on the theory theory that has passed beyond research prototypes.

Biology also offers coherence/fragmentation lessons. The modern view of naïve biology, despite commitment to the idea of naïve theories by many researchers, contains trends that undermine strong coherence. The multiple lines in biological knowledge developed by Keil and others beg the question of how much they cohere with each other. Vitalism, as described by

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[6] Thagard (2000) is a notable exception.

Inagaki and Hatano, is only a part of naïve biology, not a full, pervasive theory. And the "theory" that defines the mechanistic phase of intuitive biology is not succinctly characterized, nor is its coherence empirically measured. Inagaki and Hatano show that more primitive ways of reasoning about biology than naïve theories (based, for example, on similarity rather than biological categories) persist into adulthood. Adults also use vitalism long past the "transition to mechanistic biology." These observations are not consistent with strongly coherent "theories" and gestalt switch transitions.

Settling the coherence/fragmentation dispute requires further theory development and additional empirical work. We need better cognitive models and more precise empirical support. The metaphor of "theory" drawn from the history of science ambiguously covers both strongly and weakly systematic knowledge systems, as exemplified by Kuhn and Toulmin's debate. Specifications such as "theories embody causal notions, license distinct types of explanations, support distinct predictions, and reflect basic ontological commitments" (Gopnik & Meltzoff, 1997) are similarly ambiguous. The field must do better.

Debate over coherence vs. fragmentation is subtle. No one thinks children are completely unsystematic in their thinking about physics or biology. Furthermore, all existing views of scientific competence, when actually achieved, entail substantial systematicity.[7] The central issue, rather, is specification of the *nature* and *extent* of systematicity.[8]

Foci for Near-Future Work

Here is a list of specific suggestions for future research.

1. *Pursue detailed specification of the content development of conceptual domains*. For example, the rich empirical studies of naïve biology provide important resources for developing and testing theories of conceptual change. Furthermore, educational application will likely depend as much on domain-specific content as on general theories of conceptual change.
2. *Make contextuality a central concern*. Research on intuitive physics reveals sensitive dependence on problem context, on framing of questions, on modality (viewing, drawing, enacting), and so on (diSessa et al., 2004). In naïve biology, subjects reveal early vitalist sensitivities only when explicitly prompted. But, in contrast, no students of physics would be said to understand Newton's laws if they only thought of them when prompted. Understanding physics includes consciously knowing what concepts you are using and thoughtfully applying them. Surely this must be consequential. More generally, developmental studies consistently report "intrusion" of one way of thinking into others (e.g., psychology intrudes on biology; or weight intrudes on density). But one must ask about the relevant contextuality. When are there intrusions? Why?
3. *Assume variation across domains, and empirically validate commonalities (or differences)*. Almost all conceptual change research assumes common difficulties and

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[7] See diSessa (1993) for a knowledge-in-pieces point of view on the development of systematicity.

[8] Few if any researchers believe that intuitive ideas are deductively coherent. Yet explicit alternative forms of coherence are both rare and vague. Wellman and Gelman (1994) mention two meanings for coherence: lack of contradiction (which, as they point out, applies to a set of beliefs that have nothing to do with one another), and the idea that concepts "refer to each other" (where "reference" is undefined).

common psychological mechanism across domains. But, consider the nature of conceptual competence in various regimes.

a. Babies may be surprised by certain events (the core methodology of studies of infant conceptualization), but what is the nature of their "concepts"? Babies certainly do not use their ideas articulately to solve problems, as students use theirs in physics classes. The adult "concept" of gravity is likely a different kind of concept, acquired, in part, socially by what is read or heard.
b. Pre- and early-elementary school students integrate a large number of observations and ideas into their naïve biology, almost certainly under far less innate guidance than baby causality. Are the principles of conceptual growth and even the meaning of "concept" at all comparable at these two levels of development?
c. Consider the *source* (the thinking from which conceptual change emerges) and *target* (where the results of conceptual change are applied) for the concept of force. With respect to source, learning about force almost certainly builds out of one of the richest and most pervasively useful naïve domains. Can such a distinctive source *not* be consequential in development? Is it sensible that chemistry, say, will work just the same? Now, consider target. The context of use of the instructed concept of force is "high stress," by which I mean that one must be able to use the concept in a very wide range of circumstances, and what one does with the concept requires precise, quantitative analysis. Could that fact be irrelevant to the nature of conceptual development, compared to the "low-stress" use of mechanistic naïve biology (which develops out of vitalist biology, conservatively, by age 12), where the point is only to make rough and ready sense of the everyday biological world?

4. *Develop explicit models of constructs like "concept" and "theory," and test them against data; models need to highlight relational structure (coherence).* Researchers need to commit themselves to particular constructs, with specified meanings. What, after all, is an "entrenched belief"? I have also systematically highlighted the critical importance of understanding the nature and level of coherence in naïve and instructed competences.
5. *Accept the challenge of process validation of models of entities and change.* Toulmin argued for abandoning both snapshot models of conceptual change and snapshot validation of theories of change. Everyone agrees change is slow; but few theories exist to track the slow progress. Shockingly, almost no research on conceptual change tracks students' moment-by-moment thinking while learning. Filling in the big "before-and-after" views of change with the details of exactly what changes when may be the gold ring of conceptual change research.

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