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Conceptual Change in Physics[1]

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INTRODUCTION

In the late 1980s, a video was released which took on something of a cult status in the science education community. This video, *A Private Universe* (Sadler, Schneps, & Woll, 1989), began by showing interviews of Harvard University students at graduation dressed in their graduation robes. They were asked two questions, "what causes the seasons?" and "what causes the phases of the moon?" Of the 25 or so who were interviewed, over 20 had substantial problems answering the questions. Many confidently and eloquently expounded ideas at odds with the most elementary treatments of these questions.

One graduate after another explained that the earth is closer to the sun in the summer, in answer to the first question. It is a reasonable first guess, if one has had no instruction, but it cannot account for the commonly known fact that the southern hemisphere experiences summer when the northern hemisphere experiences winter. Further, virtually all students have been taught some form of explanation for this phenomenon in their early schooling. Further still, one of the students who gave this explanation mentioned later that he had had a course in the physics of planetary motion. In a few minutes of riveting footage, *A Private Universe* illustrated pointedly what had been demonstrated in numerous research papers on science learning: even the "best and brightest" students are not learning what educators may think they are learning from their science education.

It was a public display of what research in science education had been documenting in the literature for most of the decade, mostly in mechanics, that even after substantial instruction in physics, students have conceptual difficulties with the most basic ideas (Champagne, Klopfer, & Anderson, 1980; Clement, 1982; Halloun & Hestenes, 1985a; McCloskey, 1983; Peters, 1981; Trowbridge & McDermott, 1980; Whitaker, 1983). Ask college students how the forces compare between a bowling ball and pin when they collide, and a substantial majority of students answer that the bowling ball exerts a greater force, even after a full year of physics (Brown, 1989), when it is a straightforward application of Newton's Third Law to see that the forces are equal. Ask students to identify the forces on a moving object and, again after physics instruction, students will often indicate a force in the direction of motion, when simple applications of Newton's First or Second Laws say otherwise (Clement, 1982, McCloskey, 1983). The Force Concept Inventory (Halloun & Hestenes, 1985b) had provided a simple means for physics professors to replicate these findings with their own students. *A Private Universe* gave a final boost to a movement to transform science education to promote conceptual change.

Some of the findings and assumptions at the core of this movement have been the subject of controversy, as we discuss below, but there is widespread agreement about some of the basic phenomena:

- Many questions, phrased in a qualitative or "conceptual" way, remain difficult for students despite ample related instruction, including students who can solve standard, quantitative textbook questions about the same topics.
- Incorrect answers to these questions tend to cluster into a small number of alternatives.
- Students often show confidence in their incorrect answers.

These difficulties are clearly of serious concern to physics educators. For many, it is a surprise to find that students can solve quantitative problems without having even a basic understanding of the ideas behind the solution methods. For example, a student may be able to apply $F = ma$ accurately to find a if given F and m, but if asked to explain what the equation means might say something like: "It means that the force of an object depends on how heavy it is and how fast it's moving." This involves alternative ways of thinking about all three variables — force as a property of an object, mass as weight, and acceleration as speed.

The research of the 1980s thus showed that students could come away from instruction having memorized some facts and solution algorithms but with their conceptual understanding essentially unchanged. And so educators became interested in teaching for "conceptual change." But what does "conceptual change" mean? What are students' "conceptions" initially, and how do they change?

Most of the literature on conceptual change has understood conceptions, such as that the earth is closer to the sun in the summer, as units of knowledge; some have taken the unit at a larger grain-size in the form of a naïve theory. While this was an early view of conceptual change, and continues to be widely held in the physics education community, current research has largely come to reject unitary views of conceptions and conceptual change. In the following section, we review several perspectives on intuitive physics and on how it changes as students develop expertise. From there we will discuss our own views and some possible new directions for research.

PERSPECTIVES ON STUDENTS' CONCEPTIONS AND CONCEPTUAL CHANGE

In this section we discuss four perspectives on conceptions and conceptual change. To help present and distinguish the different views, we will describe them all with respect to a common example. For convenience, we use a simple, idealized example, which we construct based on familiar experiences in interviews and instruction.

Consider the following question: A puck slides on a frictionless surface at a constant velocity. Show any forces acting on the puck, and describe the motion of the puck.

Before instruction, a student may say and draw the following (see Figure 6.1):

> There's a downward force of gravity, and there's a force of motion in the direction it's traveling. This force of motion will gradually die away and the puck will eventually come to a stop, but not for a while since the surface is slippery.

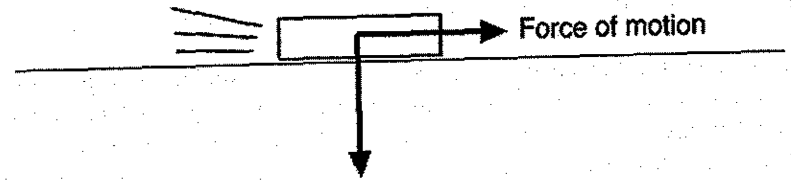

FIGURE 6.1 Student's initial drawing showing evidence of conceptual difficulties.

After instruction the student gives a different (and correct) answer, and when asked she explains (see Figure 6. 2):

> I was thinking the force would make it move, but we've learned that forces make things *change* how they move, so I don't think there's a force moving it anymore. And I know the force up by the table has to cancel the force downward by gravity, so they have to be equal and opposite. Before I didn't think we call it a force, what the table does, but we did that thing with the spring, and now I can see that the table's pushing up. Since there's no friction, that's all the forces.

We take it as well established and uncontroversial that most students would give an answer similar to the first response, prior to instruction and in many cases after instruction, and that a change to the second way of understanding the moving puck is difficult to achieve. But there are a number of different views of the nature of that change and why it is so difficult. Taking this simple before-and-after as an instance for reference, we review four theoretical perspectives. These perspectives move from a view of students' conceptions as unitary, coherent, and consistent naïve theories to a view of students' ways of talking about phenomena as highly contextual and fluid.

Students' Ideas a s Like Theories in the History of Science

Discussion in the late 1970s and early 1980s tended to focus on student conceptions as similar to earlier theories in the history of science (Driver & Easley, 1978; Posner, Strike, Hewson, & Gertzog, 1982; Hewson & Hewson, 1984; McCloskey, 1983). For example, McCloskey (1983) compared students' ideas of force and motion to medieval impetus theory, which posited "impetus" as the causal agent of motion, "injected" into a moving object and then fading or draining

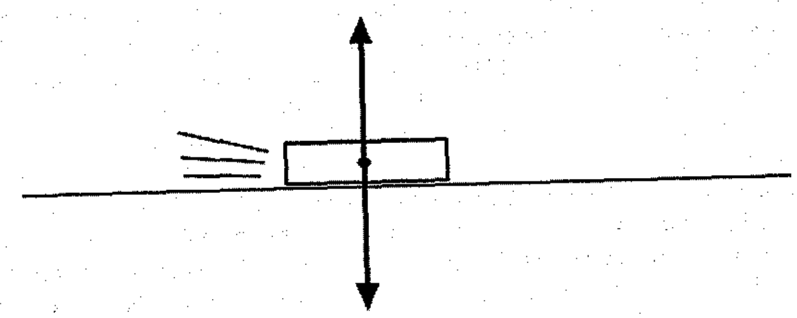

FIGURE 6.2 Student's final drawing showing evidence of conceptual change.

away. (Impetus theorists differed over whether impetus would simply fade away on its own or be drained away by impediments to the object's motion.)

From this perspective, the student's original answer to the sliding puck question reflected a naïve theory of motion, similar to the medieval impetus theories, by which motion is caused by "force" as an externally applied or internally stored influence. Thus she understood a "force of motion" as "injected" into the puck, and the motion as dying away as the force weakens. By her original theory, if there is motion, there is force. Similarly, her later answer reflected a more sophisticated theoretical framework, in which forces cause changes in motion. By her new theory, if the sum of all the forces on an object is zero, then it moves with a constant velocity, and force is not something an object can "store" or exert on itself. The change in her understanding was not simply a change in the relationship between force and motion, but a change in her understanding of what constitutes force. Her conceptual change, in this way, involves a "strong restructuring" (Carey, 1985) from one framework to another, analogous to theoretical "revolutions" (Kuhn, 1970) in the history of science (McCloskey & Kargon, 1988).

Understanding student conceptions and conceptual change in this way, as analogous to historical theories and progress, researchers outlined the requirements for such a conceptual shift to take place (Posner et. al., 1982; Strike & Posner, 1985; Hewson & Hewson, 1984). First, there needs to be dissatisfaction with the existing theory. Just as scientists would not be convinced of a new theoretical framework without compelling evidence that their existing theory is inadequate, students need to experience problems with prior conceptions in order for them to change. Then, the new theory needs to be seen as intelligible (able to be understood), plausible (believable as a potentially true theory), and fruitful (opening up new avenues of thought or investigation not possible with the old theory).

This view of students' conceptual change, then, provided an organizing scheme for education research and development. First, it shifted educators' understanding of student errors. Whereas previously students were seen as just making mistakes, now they were seen as scientists applying alternative theories to interpretations of phenomena. This helped to make sense of why students seemed "resistant" to new ideas, and it drew attention to the need to understand their existing theories: The field needed research to lay out these alternative theoretical frameworks. Second, it guided educators to understand the need for instruction not merely to present new ideas but to elicit and address students' existing ideas.

While this view got the ball rolling on considering students' content specific conceptual views as an educationally interesting area for research, the hardcore view of students' pre-instructional ideas as similar in essence to historical theories is not widely held by current researchers. First, although there is clearly overlap in how students think about motion (e.g., a continuing force is needed to keep things moving), impetus theories were developed by a community of scholars over many years and were expressed carefully in writing. Strike and Posner (1992), revisiting and revising their views on conceptual change, critiqued their own perspective as having depicted the student as too rational. They argued that rationality in theory development and selection "may be taken for granted in scientific communities" (p. 152) but not in students: "The major modifications required are to take into account the immaturity and novice standing of the learner and to deemphasize those aspects of the sociology of scientific communities that have figured in the philosophical theories of conceptual change" (p. 152).

Second, impetus theorists were deliberate and systematic in applying their principles to explaining motion in all circumstances. The theory of misconceptions did not claim students are deliberate in adhering to a set of principles; rather, they treated the apparent coherence of student reasoning as a property of the conceptual framework. Strike and Posner's critique of assuming rationality applies not only to the development of theory but to its application as well. The original theory of misconceptions asks us to believe that students tacitly adhere to essentially the same principles that impetus theorists followed with care. That does not seem plausible, and in fact there is abundant evidence that students are not typically systematic (Huffman & Heller, 1995; Maloney & Siegler, 1993; Smith, diSessa, & Roschelle, 1993/1994; Steinberg & Sabella, 1997; Tytler, 1998; Taber, 2000).

There are also reasons for concern regarding the instructional implications of the perspective of misconceptions as unitary ideas, some of which derive not from the original formulation of the perspective but from how it has been appropriated by the larger science education community. In general use, the perspective often degenerates into a general view of students as *worse* than blank slates: they are slates that have bad ideas written on them in hard-to-erase chalk. With students' prior knowledge understood as systematically misconceived, educational thinking about curriculum design and instruction focuses on systematically eliciting and confronting the ideas in that prior knowledge, the confrontation coming in the form of conflicting experience, evidence, or arguments (Nussbaum & Novick, 1982; Dawson & Rowell, 1984; Closset 1985; Thorley & Treagust, 1987). Without question, in particular circumstances this approach is effective, but it is also clear that in other circumstances it is inappropriate. Strike and Posner (1992), reflecting on their early work and what had become of it in the literature, expressed concern that the misconceptions perspective "may easily lead teachers or researchers to believe that learners enter instruction with articulated misconceptions. In fact, the actual misconception may be generated on the spot" (p. 158).

Moreover, applied systematically as the principal approach to science instruction, the strategy of elicitation and confrontation may have negative effects. Students could learn or have reinforced the notion that ideas in physics are "counter-intuitive," detached from common sense and everyday experience, with the corollary that their prior knowledge and experience is a liability. There is evidence (Halloun, 1998; Hammer, 1994; May & Etkina, 2002; Redish, Steinberg, & Saul, 1998) that by the time they are in college, many students do not expect physics to make sense, and the problem gets worse as a result of college physics courses (Redish et al., 1998).

Students' Ideas as Generated from Deeper Implicit Conceptions

We now turn to a cognitive view that is often compared to the first view of students' ideas as theories. However, while these researchers view students' ideas as theory-like in some ways, the view of theory in this context is that of coherent, underlying, and organizing presuppositions rather than specific theories as in the previous section. This work draws on numerous psychological studies exploring the naïve theories of children, adolescents, and adults. In this use, the term "theory" denotes some level of psychological coherence, which may be at an unconscious or implicit level, not the coherence of a scientific theory that is conscious and open to scrutiny.

For example, Spelke (1991) and Baillargeon (1992) have spearheaded work focusing on the "naïve theories" of infants, well before they are able to articulate their ideas using language. Through clever experiments they determine what surprises babies, based, for example, on how long they stare at a new event. From these results they have found that babies have surprisingly adult expectations: that solid objects can't move through each other, that objects that move together are likely connected, and that inanimate objects don't move on their own. This last expectation could be called a baby's "theory of inertia" (Spelke, Katz, Purcell, Ehrlich, & Breinlinger, 1994). Such a theory is clearly not the carefully articulated theory of a community of scientists, but it provides an underlying, organizing basis for perception and reasoning.

From this perspective, the student answering the puck question would not be viewed as having a coherent impetus theory, but rather as having an implicit "framework theory" (Vosniadou,

1994) consisting of presuppositions including "that 'rest is the natural state of physical objects' and 'motion needs to be explained' and that 'abstract entities such as force, heat, weight, etc. are properties of objects'" (Ioannides & Vosniadou, 2002, p. 8). These would constrain the construction of a specific model of the situation to include force as a property of the moving puck. The change to an expert understanding would be difficult because it would involve a change to the framework presuppositions.

The framework theory serves as something of a nucleus around which observations and other knowledge are organized into models in specific situations, which, as Strike and Posner (1992) argued, may be constructed on the spot. Such student models are not unitary in the sense earlier misconceptions research posited. However, once a model is constructed, it may take on generative characteristics of its own, as Vosniadou and Brewer (1992) showed may happen with student-constructed models of the earth. For example, some children think of a fishbowl with people living inside, constructed to bring together the idea of a ball-shaped earth with the framework theoretical presupposition of a universal up-and-down, and then use that model in further reasoning.

Such a perspective helps to make sense of the observations about students' answers to conceptual questions while avoiding some of the difficulties of the hardcore "theory-theory" perspective discussed earlier. This perspective also treats students' conceptions as composed of elements, such as implicit presuppositions of the framework theory, observations, metaconceptual aspects, etc. However, one prediction of this theory is that children's responses to classes of situations will be consistent, since they would access the same framework theory for a variety of instances. While Vosniadou has found such consistency in her work (Ioannides & Vosniadou, 2002; Vosniadou & Brewer, 1992), these results have been challenged (diSessa, Gillespie, & Esterly, 2004) with data showing substantially less consistency. The next perspective moves yet further away from the view of students' ideas as theories, proposing a conceptual system of many small pieces that activate, sometimes in groups, to give rise to what we see as students' ideas.

Students' Knowledge as a Collection of Primitives

The most prominent voice in this camp is Andrea diSessa and colleagues. DiSessa's framework, most thoroughly presented in his 1993 monograph, "Towards an Epistemology of Physics," directly challenges accounts of novices as holding "alternative frameworks" or "naïve theories." In this view, the intuitive physics of a novice "does not come close to the expert's in depth and systematicity" but the elements of that intuitive physics are the raw material for constructing expert understanding: "the development of scientific knowledge about the physical world is possible only through reorganized intuitive knowledge" (p. 108).

Rather than understanding intuitive physics as comprised of intuitive theories, to be confronted, overcome, and replaced, diSessa understands it in terms of cognitive building blocks he calls "phenomenological primitives" or "p-prims." They are "phenomenological" in the sense that they are minimal abstractions from experience; they are closely tied to familiar phenomena. And they are "primitive" both in how people use them, as the obviously true ideas at the bottom level of explanation, and in their role in diSessa's model of cognitive structure as "nearly minimal memory elements, evoked as a whole...perhaps as atomic and isolated a mental structure as one can find" (p. 112).

P-prims work by being "cued" or "activated," and a key difference between this account and views of naïve theories is that any p-prim may or may not be activated. In this account, the student's "misconception" that motion causes force comes about as a result of a high cuing-priority for the p-prims "force as mover" and "continuous force." The former is a primitive sense of an initial force acting on an object causing it to move, such as a shove or a toss; the latter is similar but of a force continuously applied, such as a car engine. Taking this perspective, the student's initial reasoning about the puck reflected her activation of *continuous force*, in understanding the force in the direction of the puck's motion, and the p-prim *supporting* (which does not entail a force), in understanding what the ice does to the puck to keep it from falling. Thus many circumstances cue these primitives, leading to the observations that support impetus theory interpretations of student understanding.

One would expect, however, that other questions would activate different p-prims. For example, if there were a pebble on top of the puck, a student reasoning about the forces acting on the pebble might not see any in the direction of motion, activating only *supporting* or *guiding* to understand what the puck does to the pebble. The empirical support for diSessa's view over theory-oriented views is that it is not difficult to identify circumstances that do not cue these primitives. It is common knowledge and experience for example that, sitting in a vehicle, one cannot tell how quickly it is moving without looking outside; people do not wonder why they cannot tell how quickly they are moving by the sensation of the force that is moving them. In fact, they know there is no such force, and they do not find it problematic (unless an interviewer calls it to their attention). For intuitive physics, the situation of riding in a steadily moving car is simply static, not dynamic, and the motion it involves needs no explanation. The *car's* motion needs explanation, not the passengers'.

This perspective nicely captures the contextuality observed in students' answers to questions asked in slightly different ways. It does not, however, reject robust patterns of reasoning, such as the phenomena of misconceptions, although this account is often misread to depict intuitive physics as randomly incoherent. In fact, diSessa discusses "systematicity" at length in his monograph (1993; see also diSessa & Sherin, 1998; diSessa, et al., 2004). Rather, it rejects attributing coherence as structurally encoded in the knowledge system; on this account, "systematicity" arises in a complex dynamic, to which we return below. Thus diSessa's account differs from the early views of intuitive physics much as does Vosniadou's (1994) and Strike and Posner's (1992) revisionist version: while the dynamics of novices' reasoning may produce similar results to articulate, intentional theories, the structure of intuitive knowledge is not well-compared to the structure of those theories.

The differences between diSessa's account and Vosniadou's are more subtle. Where Vosniadou posits framework presuppositions that act as "constraints" on reasoning and intuitive modeling, diSessa posits elements that are more central in the knowledge system, and so may be cued with high priority in a wide variety of circumstances. For Vosniadou, presuppositions that differ from expert reasoning must be revised; in this sense they are structural misconceptions, albeit at an implicit rather than conscious level. For diSessa, development to expertise may require the addition of new primitives, but existing primitives change only in activation priorities, not in their semantics.

Students' Ideas as Modes of Discourse

While the previous perspective treats well differences in student answers based on problem situation, there are other aspects of contextuality not explicitly dealt with in this perspective. It is the latter that we explore in this final section, a perspective that is in many ways diametrically opposed to the first perspective and that takes most seriously the contextuality and fluidity of students' ways of talking about phenomena. While earlier perspectives consider a student's "talking about" phenomena as something to be explained with some kind of model of what goes on in the student's mind, discourse perspectives tend to shy away from such mentalism. To a discourse theorist, explanations of students "talking about" phenomena are to be found in the dynamics of social interchange (Lemke, 1990; Edwards, 1993; Saljo, 1999; Hallden, 1999; Givry & Roth, 2006). Such a perspective focuses on phenomenology rather than on modeling cognition. Many discourse theorists would maintain that students' explanations, predictions, discussions, etc., are not best thought of as arising from the cognition of individual students. Rather, the appropriate focus is the discourse itself and the social and sociocultural dynamics that contribute to the discourse.

From a discourse perspective, concepts are not viewed as mental entities. Rather they are viewed as tools for social interchange. Consider the concept "banana." Saljo (1999) discusses this interesting case, showing how the concept can be different in different social contexts. When querying a botanist, the "banana" is quite easy to define, and the botanist has very little trouble classifying various fruits as a banana or not a banana. However, politically, the botanist's definition of banana causes problems. European countries that eat a lot of bananas do not want to use the botanists' definition of banana for tariff reasons — they want to exclude a kind of banana grown in the European Union that is not the typical yellow, tasty fruit one puts on breakfast cereal. "Politicians, even prime ministers, bureaucrats, businessmen, consumer organizations, ship owners and freight companies, and experts of different kinds have been involved in trying to establish what counts as a banana and what does not" (p. 82).

From a discourse perspective, the exchanges about the sliding puck are viewed not as indications of what is in the student's mind, but rather as indicative of the nature of the social exchange. Consider that the exchange likely takes place in a physics classroom, or at the very least the student knows that these are questions about physics. As such, modes of discourse pertinent to physics class are needed for this interchange. By this view, the change that took place reflects the student's having been enculturated into physics discourse, having learned to talk about Newton's first law, about free body diagrams, about frictionless surfaces, etc. By contrast, if she were talking to one of her friends about hockey, she might well say: "I wouldn't want to be hit with a slap shot — the puck has a lot of force and could really hurt." The modes of discourse in this context are different, and as such different ways of talking about moving pucks are needed. Just as banana means something different in scientific versus political interchange, what counts as a force in one social context is different than what counts as a force in another social context.

This perspective focuses attention on important social and discursive dynamics. It also recognizes the discursive contextuality of conceptions. In an everyday context, the geocentric view of the solar system is expected, and to employ a different view would be confusing. However, when discussing the solar system, a heliocentric view is needed. But even astronomers make use of a geocentric perspective when giving coordinates of astronomical bodies using altitude and azimuth. In this case the geocentric perspective is useful for discourse about particular problems.

So we see value in this discursive perspective, value in focusing on dynamics that can be undervalued in a perspective focused solely on cognitive aspects. However, the danger in such a perspective is to reify social dynamics at the expense of cognitive dynamics. In this we agree with Vosniadou, Ioannides, Dimitrakopoulou, and Papademetriou (2001, p. 395):

> Moving in the direction of taking into consideration situational and cultural variables does not necessarily mean the abandonment of the level of mental representations and its replacement with discourse analysis as suggested by some radical situationists (e.g., Saljo, 1999). A theory of conceptual change needs to provide a description of the internal representations and processes that go on during cognitive activity but should also try to relate these internal representations to external, situational variables that influence them.

Roth and Duit (2003) discuss "the structural coupling between collective conversation and individual contributions" (p. 870). While they privilege discourse in their treatment (with even the "individual contributions" considered as individual discourse), we agree that there is an interdependence, in our view between conceptual dynamics and discourse dynamics. We see the field moving toward such a consideration of dynamics at various levels as interdependent. We discuss this dynamic perspective in the next section as an integrative perspective that helps to make sense of findings from each of the previous four perspectives.

A COMPLEX SYSTEMS PERSPECTIVE ON STUDENTS' CONCEPTIONS

To review, the original perspective of misconceptions identified and called attention to the phenomena that all of this research has addressed: despite having had instruction, and often despite evident abilities at textbook problem solving, physics students continue to show sensible but naïve misunderstandings when responding to simple conceptual questions. There is wide consensus now as well that at least some of these misunderstandings vary with context (Strike & Posner, 1992; diSessa, 1993; Vosniadou 1994), as there is consensus that some naïve views students express are consistent with expert understanding (Clement, Brown, & Zietsman, 1989; Minstrell, 1992, 2000). The points of debate over conceptual phenomenology concern the extent to which students' reasoning is consistent with a core set of tacitly held ideas, and the extent to which it varies with question or context.

In our view, there is strong evidence at both ends of this phenomenological spectrum. There are clearly "systematicities" in student reasoning, to use diSessa's term, that appear across a wide range of circumstances, as research since the first papers on misconceptions has documented. It is also clear "that students may change their local, situational models, move from one misconception to another, or even be internally inconsistent" (Vosniadou, 1994, p. 65), as research has amply documented as well. An adequate model of intuitive knowledge must account for the full range of established phenomena.

The field has been making progress in constructing such a model, reflected particularly in diSessa's and Vosniadou's work, and we see this progress as toward a complex systems account of knowledge and learning. Our purpose in this section is to promote that progress. We will review the concept of a complex system, and then we will argue that a complex systems perspective can integrate findings from previous work. In particular, we will argue that, couched within a complex systems approach, the differences in diSessa's and Vosniadou's models mostly disappear, and discourse dynamics can be seen as theoretically continuous with conceptual dynamics.

Complex Systems

Complex systems theory concerns dynamical systems in which there are interactions among components that include feedback, such that what happens to one part of the system can affect another part, which can then affect the first part. This feedback makes the system *non-linear*, such that a small change can lead to a disproportional effect. A complex system need not have many components — a double pendulum is a simple non-linear dynamical system — but a great deal of complex systems research involves systems with many components. In recent years there has been growing interest in modeling cognition and development as a complex, dynamical system (Thelen, 1992; Thelen & Smith, 1994; Bogartz, 1994; van Geert, 1994, 1998).

One of the central ideas in a complex systems perspective is that robust order and structure can emerge from the interaction of a large number of random interactions, without the overall direction of an intelligent agent, much as tossing a coin billions of times reliably results in very close to 50% heads and 50% tails. Structure and coherence can emerge out of a dynamic system of interacting simpler agents.

To help get a sense of this, consider a cocktail party to which a number of people are invited. If you look into the cocktail party, in which people are free to move about, you would likely see them organize into a collection of small groups. No one has told the partygoers to get into groups; it arises from individuals making independent choices of where to place themselves. If you look later, it still looks this way, although if you look closely the groups have changed — some no longer exist, others have grown larger, etc. If you look at another party, the actual groups that form and the places in which they form after the same amount of time will vary from the first party, although one can predict with near certainty what the general look of the party will be. Of course, environmental factors can influence these results. If tables or bars are present at the cocktail party, it is a sure bet that groups of people will tend to gather around these (although not all tables will have groups, and for any given table it may be impossible to predict in advance whether it will have a group or not, how many will be in the group, who will be in the group, etc.). If the tables are rearranged, this will have an effect on the arrangement of the groups.

The cocktail party can be taken as a metaphor for many complex systems. In general, after a certain amount of time, complex dynamic systems may "settle" into stable patterns, or "attractors." The patterns may be robust, but they are not fixed features; larger scale patterns arise from the independent actions and interactions of individual elements at a smaller scale. In one respect, however, this example may be misleading. One might understand it as a property of individuals that they prefer to be in groups of a certain size, and so there would be a direct correspondence between small scale features and large scale patterns. In most dynamic systems, properties of elements do not correspond so directly with large-scale patterns. For example, it is not a feature of people in cars that they hope to be in traffic jams, but that is another reliable result of many individual choices under appropriate conditions, with robust, predictable patterns (e.g., that the location of traffic delay moves backwards along a highway).

Many phenomena are well-modeled with a complex systems approach, from disease propagation to cellular function, and chemical reactions to stock market pricing. Dynamic systems occur over a wide range in size and stability—sound, smoke rings, hurricanes, and trade winds are all dynamic processes that arise from a common set of fundamental mechanisms at the level of air molecules. Research on how people think about these systems has shown a tendency toward reasoning in terms of unitary, centralized structures (Resnick, 1996; Wilensky & Resnick, 1999; Wilensky & Reisman, 2006). That is, people often think that stable patterns come about because of inherent, fixed properties of the system.

Such reasoning is evident also in considering student "misconceptions" as unitary entities. As discussed below, considering students' conceptual thought as a complex dynamic system does not in any way deny the existence of stabilities in student reasoning (and the need to understand these stabilities). But considering students' conceptual thought as a complex dynamic system accounts for observations that a unitary account finds problematic (e.g., students answering one way in one context and a different way in a different context); it positions conceptual dynamics as theoretically continuous with discursive and sociocultural dynamics; and it brings to the fore new and potentially fruitful research directions.

Complex Systems Theory and Conceptual Change

While there has been a great deal of interest in complex systems within cognitive science, there has been little discussion of its application to theories of conceptual change. It is in this light that

we view the promise of diSessa's and Vosniadou's frameworks as the beginnings of complex systems accounts.

Complex systems theory describes the full spectrum of phenomena in the literature on conceptual change, from the robust, lasting patterns of reasoning to fleeting, context-sensitive variability. Each may be described in terms of dynamic cognitive structures, arising from the interactions of smaller conceptual elements or resources (which themselves develop from even smaller elements). The nature of complex systems is such that these dynamic stabilities would generally develop. However, it may be the case that these stabilities or structures dynamically dissipate and reform rather quickly in different contexts. Or it may be the case that these structures remain largely the same across a wide variety of contexts. The complex systems perspective argues that such emergent stabilities generally develop, but the nature and extent of such structuring is a matter for empirical investigation. Our goals for the remainder of this chapter are to sketch possible connections between dynamic systems theory and students' conceptions and learning. We suggest that dynamic systems can make sense of established ideas and, more important, that it points in particular directions that might advance research on conceptual change.

Core Features of Complex Systems

Some widely applicable ideas of complex systems include the following: intrinsic dynamism, non-linearity, emergent structures, and embeddedness (Wiener, 1961; von Bertalanffy, 1973; von Foerster, 1996; Powers, 1973; Thelen & Smith, 1994; van Geert, 1994).

Intrinsic Dynamism

Elements of the system are in constant and dynamic interaction. One type of this remaining the same but changing is "dynamic equilibrium." Systems in dynamic equilibrium are "thing-like" in that in many respects they remain the same, but they are not "thing-like" in that the mechanisms that produce them are dynamic. It is much easier to think of a person as an enduring individual than it is to think of the processes that are in dynamic flux, producing the perceptually stable person. In many cases it is appropriate to ignore the dynamics and treat the dynamic system as having an enduring identity. However, when the orientation is toward changing the system, as in conceptual change, treating the system as unitary is inappropriate.

Non-linearity

Some dynamic systems are *linear* such that perturbations lead to proportional results: double the tension on a cord in a system of pulleys, for example, and the tension is doubled throughout. Non-linear systems are characterized by feedback such that a change in one part of the system causes change in another part which then causes changes in the original part. This generally leads to non-proportional results much larger or much smaller than the original perturbation.

For example, consider a simple ecosystem of rabbits and grass (see Figure 6.3). If the rabbits get enough grass to eat they will have the energy to live and to reproduce. However, if the rabbits do not have enough to eat, they will start to die of starvation. If the population of rabbits gets too high, they will eat too much grass. This will decrease the population of grass to the point where the rabbits will not have enough to eat. Many rabbits will die of starvation. Enough rabbits may die that the grass can grow almost without check, greatly increasing the population of grass. In this environment of plenty, the remaining rabbits (if there are any!) will flourish, increasing the rabbit population, returning us to another surplus of rabbits that will eat too much grass.

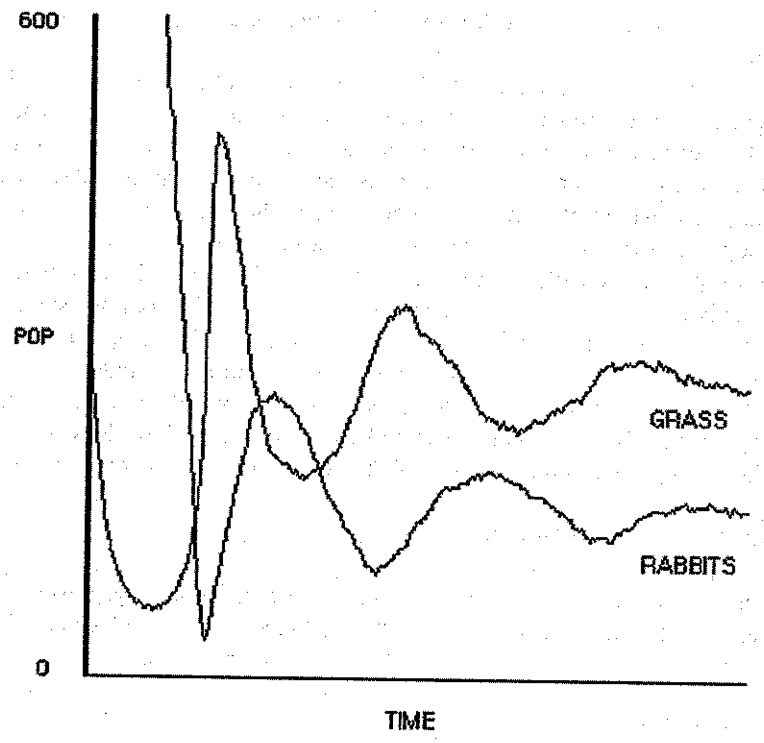

FIGURE 6.3 The populations of rabbits and grass swing through extreme highs and lows before, in this case, tending toward dynamic equilibrium values (an "attractor state"). From a NetLogo simulation (see Wilensky, 2001).

Changing the number of rabbits leads to a change in the amount of grass which then affects the number of rabbits, and so the system is non-linear. Still, it can produce predictable results and a dynamic stability. In simulations of this simple ecosystem, depending on the starting conditions the rabbit population may die out in one of the early oscillations, or the system may settle into an "attractor state" with a dynamic equilibrium of rabbits and grass, as shown in Figure 6.3. Whether the system reaches that equilibrium can be sensitive to the starting conditions, and may do so in ways that may be counter-intuitive: Start with a little more grass for the rabbits to eat, and the rabbits may die out. Otherwise, however, the equilibrium is stable with changes of rabbits or grass: The addition of a group of rabbits, for example, will upset this equilibrium, but after some time the system will return to the same state. And, of course, the dynamic would be entirely different if the change is to introduce a single pair of foxes. Similarly, the conceptual system seems to be non-linear — under many circumstances, even a great deal of instruction can lead to little change, while in other situations small influences can lead to major insights.

Emergence

Because elements of the system are in constant and dynamic interaction, structures and patterns emerge as a result of these dynamics. Such structures are typically not predictable based on the individual elements of the system, and so the structures need to be studied at an appropriate grain size. In the cocktail party system, small groups emerge naturally as a result of the social

dynamics of the party. Similarly, students' conceptions may be understood to emerge from the dynamics of smaller conceptual pieces.

Embeddedness

Complex systems often have the feature that they are embedded within complex systems at a larger scale and have complex systems at a smaller scale embedded within them. Consider the human body, for example, with its circulatory, nervous, digestive, immune and other systems. Each can be modeled as a complex system in itself, but each of course is composed of cells, which are also complex systems, and they are all part of the larger system of the body as a whole. On a still larger scale, the nervous system of a modern day human is a result of the dynamic processes of evolution; at still lower scales are the systems of chemical interactions. Depending on the clinical or scholarly matter at hand, it may be essential to consider more than one level of organization in understanding bodily phenomena.

In a similar way, research on cognition could expect multiple levels of organization, from neurons to simple conceptual components (such as p-prims) to more elaborate conceptions to minds as complex systems. On still larger scales, this approach could be continuous with models of social and cultural dynamics, again as complex systems but at a larger scale of organization. In terms of conceptual change, dynamics at various levels are embedded in each other and interact — evolutionary, neural, protoconceptual, conceptual, metaconceptual, social, sociocultural, etc. In investigations of students' conceptions, often the conceptual level is predominantly (and often appropriately) the focus. However, in instructional planning, typically there is explicit or implicit recognition that other levels must be considered as well.

Connections and Refinements to Existing Research

It is not difficult to find alignments between ideas from complex dynamic systems and existing research on conceptual change. As we have discussed, complex dynamic systems show stabilities, and the stabilities can be robust, which provides an account of the observation that brought conceptual change ideas to the fore in physics education — that patterns in students' reasoning can be difficult to change. This account is clearly similar to both diSessa's and Vosniadou's, with conceptions understood as resulting from knowledge elements at a lower level of organization; it is closer to diSessa's in that the lower level is itself dynamic, in contrast to Vosniadou's view of constrained presuppositions.[1] In its non-linearity, the account matches the familiar experience that amount of instruction is not proportional to amount of conceptual learning. Moreover, a complex systems account leads easily to views of situational and social dynamics at larger levels of organization.

While we argue that the field has been moving toward a complex systems perspective on conceptions and conceptual change, none of the perspectives reviewed previously takes a full-blown dynamic perspective. The misconceptions and discourse perspectives tend to privilege one level of organization in their accounts, of conceptions or of discourse practices, often to the implicit or explicit exclusion of consideration of dynamics at other levels. For example, radical discourse theorists often say explicitly that consideration of conceptual dynamics is misguided (Edwards, 1993; Saljo, 1999; Roth & Duit, 2003). In our view, adopting a complex systems perspective can incorporate existing ideas into an integrative framework. The phenomena of misconceptions and of discourse can be understood as emergent from complex dynamics at different levels of organization.

Vosniadou's and diSessa's accounts both describe complex knowledge systems, taking student ideas in particular situations as emergent phenomena arising from the activity of lower-level knowledge elements. Each, however, posits a bottom level to the cognitive structure. In Vosniadou's theory, the bottom level is comprised of the framework presuppositions, such as that "space is organized in terms of the directions of up and down" (1994, p. 49), or that "hotness is a transferable property of physical objects" (p. 48), which act as constraints on further reasoning. Conceptual change requires revising the presuppositions. In diSessa's view, the bottom level is comprised of phenomenological primitives, such as "force as mover" or "Ohm's p-prim," which may or may not be activated in any particular moment. They are not constraints on reasoning, because they may or may not be cued at any particular moment. But as primitive elements — "atomic and isolated" mental structures (1993, p. 112), once formed they are not themselves subject to revision. For diSessa, conceptual change requires revising, not the primitives, but how and when they are activated.

DiSessa's model is of a complex system, taking p-prims as the fundamental elements. Adopting a complex systems perspective more broadly, p-prims could be seen as stable dynamic structures, as might Vosniadou's presuppositions. In this way, the two theories could be understood as different possible dynamics of a system. P-prims describe structures that are more stable than presuppositions, which in Vosniadou's account can ultimately change; presuppositions act like p-prims in the limit of universally high cuing and reliability priorities — think of Ohm's p-prim, which diSessa describes as more "central" than others, as essentially always cued in contexts that invite thinking about effort or resistance. The system could admit other possible dynamics as well, such as structures with both properties — essentially always cued and too stable to disrupt — so as to act as 'permanent' properties of the system.[2] The important point here is that, framed as emergent structures in a dynamic system, there is no principled reason to suppose the system must act only one way or the other. One possible outcome of the debate, then, is that one or the other version of the dynamic may apply within different regions, and the question for research becomes one of delineating those regions.

In this way, too, a complex systems approach helps answer questions that arise within each of these accounts. In Vosniadou's account, the framework presuppositions act as fixed constraints to the dynamics of the system. What happens to change that? There are several possibilities within a complex systems account, of presuppositions having some kind of accessible internal structure, some kind of activation priority like diSessa's p-prims, or as we noted having their output suppressed.

In diSessa's framework, p-prims are varied to the point that they can seem like different kinds of cognitive objects. Ohm's p-prim, for example, has a very general schematisation of a causal agent acting through a resistance to produce a result (p. 217), which may apply to a wide range of phenomenology — from pushing a box across the floor to giving students continuous encouragement to work hard. Some other p-prims could be seen as general in this way; *continuous push* could be understood to schematise any causal agent maintaining an effect. But other p-prims, such as *Force as spinner*, can apply only to a much more narrow set of circumstances (Brown, 1993; Redish, 2004). Moreover, Ohm's p-prim involves schematisations of resistance and effort, ideas that are repeated in other primitives in diSessa's account. A number of primitives involve similarities in meaning, suggesting that it might be fruitful to look further into the substructure of p-prims rather than treating them as atomic and isolated, as diSessa has mostly done so far.

Thus we see a complex systems perspective as allowing a synthesis of prior research in conceptual change. In the following section we further discuss how this perspective can make sense of a number of well-established findings in the literature on conceptual change in physics. We then explore what it would suggest as promising directions for future research and instructional practice.

A COMPLEX SYSTEMS PERSPECTIVE ON EXISTING AND FUTURE RESEARCH AND INSTRUCTIONAL PRACTICE

For the past 25 years, research in conceptual change has been organized primarily by the ways of thinking introduced in the early research on misconceptions and alternative frameworks: Students have ideas, sensible but incompatible with scientific expertise, and these ideas pose difficulties for constructive conceptual change. The first task for research, then, is to identify those ideas, and that has been a powerful organizing scheme.

A researcher looking for a new, do-able and publishable project needs only to identify a domain of science in which there has not been sufficient charting of students' misconceptions and difficulties. Existing research offers a range of methodological models for how to proceed, such as by posing problems within that domain in clinical interviews, observing students' work in classroom interactions, and designing instruments to assess conceptual understanding. The best work employs a range of these methods, such as starting with observations to find likely candidates of misunderstanding, designing clinical interviews to explore those candidates, and gathering qualitative data of the range of possible lines of reasoning. Thus the incorrect ideas discovered in observations and interviews provide ideas for item construction in the instrument, in how to pose questions and what possibilities to include in the choices for answers. (For a bibliography of several thousand articles identifying misconceptions and difficulties, see Duit, 2006.).

In these respects, then, the question "What are students' misconceptions" (or, many studies in physics ask, "What are students' difficulties") has been extremely generative; we might describe it as paradigmatic. As thinking moves on from the misconceptions paradigm, however, the need opens up for lines of inquiry that have the same fertility and generativity for research.

Our purpose in this section is to lay out a research agenda from within a complex systems paradigm, illustrating its generativity. We begin by revisiting established empirical findings, to reconsider them from within a dynamic systems perspective. We then turn to promising new areas for research.

Established Findings and Implications from a Complex Systems Perspective

The core findings and implications from conceptual change research may all be re-expressed in terms of complex dynamic systems. We discuss several of these established findings below.

Students' Conceptual Dynamics Exhibit Conceptual Attractors

One characteristic of students' conceptual dynamics that became salient early on is that often inappropriate ideas are comparatively undisturbed by instruction (Champagne et al., 1980; Clement, 1982; Halloun & Hestenes, 1985a; McCloskey, 1983; Peters, 1981; Trowbridge & McDermott, 1980; Whitaker, 1983). For example, Brown (1989) discusses students' conceptions of force, presenting evidence that a conception of force as a property of objects explains much evidence from diagnostic tests focusing on the interactions of objects (e.g., a bowling ball striking a bowling pin), both before and after physics instruction. Objects that have more force then exert more force. In many cases these conceptions of physical phenomena are similar even across cultures (Driver, Squires, Rushworth, & Wood-Robinson, 1994).

From a complex systems perspective, these are strong conceptual attractors, dynamically emergent stabilities. We would expect to find a range in the phenomena of stability, from momentary thoughts to long-lasting patterns of reasoning; we would expect to find patterns that tend to emerge under specific conditions and others that emerge in a wide variety of situations.

This enables a dynamic perspective to embrace both the stability of students' ideas as well as the fluidity and contextuality of their ideas.

Instruction Must Pay Attention to Conceptual Attractors

Since the earliest articles on conceptual change, researchers have argued that instruction must pay attention to student conceptions. A complex systems perspective provides a new lens on earlier work and its implications. It predicts that learning will not be a linear accretion of knowledge, whether through instruction or through induction from experiment. Even after extensive instruction, students' reasoning may remain unchanged, as so many studies have shown. On the other hand, however, in some situations brief interventions can have dramatic effects (Duckworth, 1987; Mayer 1995; Clement 1989; Rosenberg, Hammer, & Phelan, 2006).

As we have noted, there is an extensive literature on instruction taking student conceptions into account (Duit, 2006), especially within physics. Reviewing this work from a complex systems perspective gives new insight into the effectiveness of this perspective.

For example, Hewson and Hewson (1983) critiqued traditional instruction as simply introducing new information without paying attention to students' existing ways of making sense of ideas related to the concept of density. They found significant improvement from encouraging students to consider their existing ideas. Minstrell (1984) found that even when he took substantial extra time to carefully outline the logical arguments for Newton's first law in a high school physics class, most students reverted to naïve ideas later. When he involved students in activities that had them consider their naïve ideas, most correctly answered conceptual questions on Newton's first law toward the end of the year. McDermott and Shaffer (1992; Shaffer & McDermott, 1992) had similar results from helping students consider their own reasoning about electricity and electrical circuits.

In each of these cases, large interventions of one kind had little effect, and improvement resulted from changes in the kinds of interventions rather than simply the extent. From a complex systems perspective, these early studies all illustrate a familiar occurrence in non-linear dynamics — the results in student learning were not proportional to the instructional "perturbation."

In each of these cases, a central aspect of the new instructional dynamic was that it engaged students in reflection about different perspectives; students became aware of different possibilities for making sense of the phenomena they were studying. White and Frederiksen (1998) focused explicitly on this aspect of their instructional design, of the role of metacognition in student learning and conceptual change, in the context of their *ThinkerTools* computational environment for middle school students to explore forces and motion. In other words, the system involves not only conceptual knowledge but metacognitive knowledge as well, and we may frame White and Frederiksen's findings in terms of interdependence is among embedded conceptual and metacognitive stabilities.

Students' Conceptual Dynamics Exhibit Fluidity and Contextuality

While there is clear evidence of conceptual attractors, there is also clear evidence of contextual sensitivities (diSessa, 1993; Maloney & Siegler, 1993; Smith, diSessa & Roschelle, 1993/1994; Mestre, Thaden-Koch, Dufresne, & Gerace, 2004; Tytler, 1998; Hammer, 2004). For example, Maloney and Siegler (1993) studied students' reasoning on a variety of kinetic energy and momentum problems to show evidence that they held multiple, conflicting conceptions, and the particular conception they applied depended on the problem they were shown. Elby (2000) showed that students were more likely to reason about graphs as though they are pictures, such as to misinterpret a velocity graph as depicting position, when the graphs contain "compelling visual attributes" such as a pointed maximum or an intersection. Parnafes (under review) recently observed students describing a motion as "fast" in the sense of frequency when observing a high frequency, low amplitude oscillation, but shifting to describing another motion as "fast" in the sense of linear velocity.

These studies illustrate a phenomenology of variation among different local stabilities: Ask students one question, and they show one, often robust pattern of reasoning; ask them a different question or change the context, and the same students show a different pattern. This mix of stabilities and variability is quintessential to complex systems. As we have emphasized, however, the variability in complex systems is not without structure, and knowledge-in-pieces accounts do not present reasoning as incoherent.

Instruction Can Draw on Fluidity and Contextuality

A complex systems perspective entails a view of knowledge and reasoning in terms of manifold resources that can activate in various ways at various times, rather than of unitary, systematic (mis)conceptions (Hammer, 1996, 2000). For teachers, it means thinking of student reasoning in any particular moment as possibly only a local stability, and it implies the possibility of other stabilities, of different sets of resources becoming active in other contexts. This suggests instructional strategies to help students find other possibilities in their existing knowledge, to focus attention on building from productive resources, rather than to focus primarily on eliciting and confronting wrong ideas. As well, it suggests caution in interpreting students' correct reasoning as evidence that they "got it."

The same students that have strong non-Newtonian intuitions in some contexts have strong Newtonian intuitions in other contexts (Clement, Brown, & Zietsman, 1989). Students do not only have wrong ideas or misconceptions, and a constructivist understanding of learning holds that sophisticated understandings must develop from the same conceptual system that produces misconceived responses. The underlying basis of the use of analogies and models (Gutwill, Frederiksen, & White, 1999; Dagher, 1998; Gilbert & Boulter, 2000; Clement & Steinberg, 2002; Clement, chapter 16, this volume) is that students will have conceptual resources in one context that they can use in a different context. In other words, analogies and models may be understood in terms of drawing connections among different parts of the cognitive system, and these connections may give rise to new stabilities.

For example, students tend to think of a spring as exerting a force back on a hand that compresses it. That intuition can serve as a conceptual "anchor" for students to recognize the upward force by a table on a book, and an instructor can facilitate this connection by presenting bridging analogies, such as a book on a bendy table (Minstrell, 1982). Brown and Clement (1989) and Brown (1993) show that this is not an abstract transfer (upward force in one context means upward force in another context), but rather that the construction of a conscious explanatory model in the table context (the table as microscopically springy) allows the attachment of appropriate intuitions to that context. When such bridging analogies and explanatory models are used in classroom instruction, students show significant gains on conceptual questions (Clement, 1993).

That analogies and models can be helpful in instruction is another strong result of the literature (for reviews see Duit, 1991; Dagher, 1998). However, the traditional view of analogy is rather static. In a "structure-mapping" account (Gentner 1983, 1989), the analogical base is construed to have a well-defined structure from the outset that is mapped to the target domain. For example, an analogy may map the structure of the solar system (the base) to an atom (the target), with a large central body and orbiting smaller bodies, with superficial features including the size and luminescence of the sun irrelevant.

From a complex systems perspective, the process can be much more dynamic, a fluid recruiting of conceptual resources from different parts of the system that then interact and settle into new patterns. The structure of the base need not be so stable as to remain constant in the process; the "base" may not exist prior to the analogy. Atkins (2004) presented a dynamic view of analogical reasoning in her analyses of several case studies. She connected the study of analogical reasoning to research on categorization, arguing that the generation of an analogy is essentially the nomination of a category, and that it is often misleading to expect a mapping from an intact, stable base to a target. As categories can be ad hoc, such as things to take from your house in a fire (Barsalou, 1987), analogies including analogical bases can be as well. Recent work on ongoing model construction, critique, and revision is consonant with this view as well (Clement, 1989; Wong, 1993a, 1993b; Dagher, 1998; Frederiksen, White, & Gutwill, 1999; Gilbert & Boulter, 2000; Clement & Steinberg, 2002; see also Clement, chapter 16, this volume, for a much more extended discussion of this area of research).

While some segments of the community have focused attention on conceptual change, other segments have focused attention on students learning science as inquiry. Research on analogies in physics classes, for example, has focused almost exclusively on instructional analogies, in the interest of promoting conceptual change, but a small number of studies have focused on understanding and promoting student abilities to generate and work with their own analogies (Wong, 1993a, 1993b; Atkins, 2004; May, Hammer, & Roy, 2006). Conceptual change and inquiry are often treated as distinct objectives (National Research Council, 1996), but a complex systems perspective would suggest they are interdependent, much as White and Frederiksen (1998) treated them in developing and analyzing the results of their *ThinkerTools* curriculum. In this way, a complex systems perspective supports views of the importance of meta-level aspects of student reasoning (Hennessey, 2002; Gunstone, 1992; Andre & Windschitl, 2002; Hewson, 1985).

Research on student epistemologies has begun to consider them as dynamic systems as well, comprised of manifold epistemological resources that are again context sensitive in their activation with multiple stabilities (Hammer & Elby, 2003; Redish, 2004; Rosenberg et al., 2006), such that students who approach learning as memorization in one moment may approach it as a personal construction of meaning in another. These epistemological resources may be seen in dynamic interaction with conceptual resources. For example, a stable Newtonian concept of *force* may involve a stable commitment to principled consistency in reasoning, because there are many apparent inconsistencies with that concept in unrefined intuition (Hammer, Elby, Scherr, & Redish, 2005). Without a commitment to consistency, a student would experience no need to reconcile those inconsistencies (diSessa, Elby, & Hammer, 2002).

New Emphases for Research

We have discussed existing work as seen from a complex systems perspective. A fully dynamic perspective, which we argue the field is moving toward, also has a number of implications for what may be generative areas for further research.

Identifying Productive Resources

With the extensive body of literature on student difficulties and misconceptions in place, the field would also benefit from complementary research to identify possible conceptual progenitors of expert understanding in students' intuitions. In a sense, this work is already underway, as research in curriculum development to address identified student difficulties invariably involves instructional strategies of guiding students toward helpful prior knowledge (Heron, 2004a, 2004b). But relatively few studies have made it an explicit agenda to identify helpful "facets" (Minstrell, 1992; Minstrell, 2000) of students' prior knowledge, the "preconceptions that are not misconceptions" (Clement, et al., 1989), such as how thinking about compressing springs provides useful conceptual resources for reasoning about the upward force by a table on a book. The possibilities are as rich as they have been for identifying misconceptions and difficulties.

Studying Transitions Among Multiple Stabilities

Naïve reasoning about springs and tables illustrates the phenomenon of multiple stabilities: Thinking about an object sitting on a visibly compressed spring, people think of the spring as pushing up; thinking about an object on a table, people think differently. The strategy of a bridging analogy is about facilitating a transition in student thinking from one stability to the other. We see a promising emphasis for new research in describing the dynamics of transitions from one to another, both as it happens spontaneously and as it may be facilitated by instruction.

To use Parnafes' (under review) work as an example, recall that students who look at a small amplitude, high frequency oscillation are likely to speak of the motion as "fast" in the sense of frequency, and those who look at high amplitude, low frequency oscillations are likely to speak of "fast" in the sense of translational velocity. What might be the dynamics of their transition from one meaning of "fast" to the other? Perhaps there are interesting phenomena in their reasoning about middle frequencies and amplitudes; is it possible for small, subtle cues to tip students into one meaning or the other? Similarly, Elby's work (2000) showed different patterns in students' interpretations of graphs depending on the presence or absence of eye-catching features. How subtle can the difference be and still show the correlation?

Studies of conceptual dynamics are more challenging, methodologically, than identifying misconceptions, but work of this kind has already been underway. Research in cognitive psychology began to emphasize microgenetic studies in the 1990s, trying to identify particular developmental changes as they occur, with a high density of observations "from the beginning of the change to the time at which it reaches a relatively stable state" (Siegler & Crowley, 1991, p. 606; see also Siegler, 1996; Siegler & Svetina, chapter 5, this volume). That "stable state" need not be developmental, in the sense of a new, fixed part of the learner's reasoning; it might be one of multiple possible stabilities, and the research could focus on understanding the extent of those stabilities and the nature of the transitions from one stability to another.

Developing Multi-dimensional Accounts of Learning Dynamics

Leander and Brown (1999) discuss six dimensions of embedded dynamics they identified in a microanalysis of a 20-minute discussion in a high school physics class. These dynamics included focal, conceptual, discursive/symbolic, institutional, social, and affective. The focal dynamics were generally unstable, with the focus of the discussion moving between a pendulum, an object on a spring, a tossed pencil, a baby on a rubber band, etc. The conceptual dynamics exhibited substantial stability within individuals, but substantial variability between individuals, leading to much talking past each other. Discursive/symbolic modes or forms of communication varied widely between the teacher and students. Students tended to animate stories about particular situations while the teacher tended to focus on abstractions, bringing in individual situations as examples of these abstractions. Institutional stabilities and instabilities were imposed by institutional structures and policies such as grades, syllabi, standardized tests, etc. This discussion came during a test review, and this institutional stability had noticeable effects on the discussion. Social stabilities and instabilities were exhibited in interpersonal alignments and misalignments, and affective stabilities and instabilities were exhibited in various expressions of emotion such as frustration, laughter, withdrawal, etc.

Research on learning generally identifies a specific target of investigation, be it conceptual understanding, epistemologies, affect, or social dynamics. Educators widely recognize these various aspects are interdependent. For example, research from an explicitly cognitive orientation often has students working in groups in order to take advantage of the social dynamics, while work from a social or sociocultural perspective will often involve students in consideration of discrepant events. In most cases it is difficult to discern the underlying theoretical orientation simply by observing the instruction. Still, there has been relatively little explicit discussion (Cobb, 1994; Roth & Duit, 2003; Vosniadou et al., 2001), largely because it is difficult to conceptualize and articulate the nature of these interdependencies. A complex systems perspective may help provide a theoretical framework.

Investigating Non-linear Conceptual Growth

The almost unquestioned assumption in most instruction is that if we want students to learn more, we need to teach more *at a faster uniform pace*. If we need to build a brick wall faster, we need to put the bricks on top of each other at a faster uniform pace. However, if students' conceptions form a complex dynamic system, we might expect progress in the system to be non-linear; we might think of an analogy to population growth or to phase change rather than to adding bricks in the wall. Instructionally, this would mean expecting a period of slow growth at the outset with more rapid progress later, as ideas connect to and build on the initial conceptual understandings. This is not to say that students are not learning much at the beginning (we would argue that a great deal of learning is occurring as students begin to form initial conceptual understandings), but rather that the number of topics covered in a typical textbook is likely to be less. It would also suggest that to impose a linear rate (in terms of topics per unit of time) may not provide sufficient time for meaningful learning at the outset. This would have implications for what happens later, except for those few students who for whatever reason were already at a place in their exponential learning where their rate of learning matched the pace of instruction, and thus they were able to keep up meaningfully.

We do not know of published studies explicitly taking such an exponential learning perspective, but there are some indications that such an approach could be beneficial. Anecdotal accounts include Max Beberman, one of the leaders of the "New Math" movement and a skilled mathematics teacher who focused closely on students' ideas in his own instruction. He took this approach with some middle school students and found that after one semester he was woefully behind other classes. After a year he was slightly ahead, and after two years he was far ahead of the other classes (Easley, 1993, personal communication). Don DeCoste, a former high school chemistry teacher and current chemistry professor at the University of Illinois, obtained similar results in his own teaching. After one semester teaching high school chemistry (and not moving on until students had a good conceptual grasp), he was well behind the other classes, but after one year he was slightly ahead (DeCoste, 2003, personal communication). Gautreau and Novemsky (1997) discuss the use of non-mathematical, conceptual physics to begin their physics instruction (van Heuvelen's 1991 OCS physics). Even though the experimental classes did not get to practice quantitative problem solving until substantially later in the semester than comparison classes, on tests of quantitative problem solving later in the semester the experimental classes performed substantially better. Benezet (1935) delayed instruction of computational algorithms until sixth grade, focusing in the early grades instead on more conceptual aspects of mathematics such as estimation of quantities. He found the experimental students caught up to traditional students in computation after one year, but they vastly outstripped comparison students in ability to think mathematically. This lesson has gone largely unheeded in the United States. Hiebert, Stigler, Jacobs, Givvin, Garnier, Smith, Hollingsworth, Manaster, Wearne, and Gallimore (2005) critique mathematics instruction in the United States, based on the *Third International Mathematics and Science Study*. In the United States, which did poorly in this comparison, they found that 53% of the time in mathematics classes was spent on review of rather rote procedures, while in other countries, which performed better, much less time was spent on review and much more time on introducing new conceptual material.

Exploring Phenomena and Models at Multiple Scales of Structure

Complex systems are often characterized by a range in dynamical and structural scales. Recent research has focused on a number of interesting properties shared by many self-organizing networks such as the World Wide Web, social networks, or chemical reactions in organisms.

One common property is "self-similarity" (Song, Havlin & Makse, 2005). Like snowflakes, coastlines, trees, and other fractals, many networks have similar structure across a wide range of scales. Look at a branch of a tree coming off the trunk, and it has branches of its own, which have branches, a fractal structure such that a portion of the tree is similar to the tree as a whole. For networks, self-similarity would entail elements clustering in patterns such that at larger scales the clusters are similar to the elements at the smaller scales.

Many of these networks are also "scale free" in another sense: There is a pattern in the connectedness of elements in the network such that a small number of elements have many connections, and a large number of elements have few connections. Specifically, the probability that a particular node in the network has k links to other nodes is proportional to λ/k^{l}, where λ is a constant that is typically between 2 and 3 for naturally occurring networks (Barabási, 2002). The few nodes with many links act as hubs, and these networks also tend to have "small-world" connectivity in that it does not take many connections to get from one node to another in the network (Strogatz, 2001). (Six degrees of separation claims small-world structure in society in that nearly all people are connected to each other by no more than six social connections.)

Ideas from network theory are beginning to influence cognitive science. Steyvers and Tenenbaum (2005), for instance, examined the structure of three types of semantic networks: word associations from a database collected from 6,000 subjects (Nelson, McKinney, Gee, & Janczura, 1998), *Roget's Thesaurus* (Roget, 1911), and WordNet (Miller, 1995). In each case they found a nearly scale-free pattern of connections as well as small-world connectivity.

Perhaps these ideas could be generative for research on conceptual change, with its range in scales of phenomena and the range in structural scales of cognitive entities posited to account for those phenomena. Of course, the members and links in the network relevant for research on conceptual change are not easy to identify, but research has already nominated structures at various scales, including diSessa's p-prims and Vosniadou's presuppositions. Brown (1993, 1995) described a hierarchy of structures ranging from core intuitions to conscious models to verbal-symbolic knowledge. A network theory perspective suggests looking for invariances up and down these scales.

Supposing self-similarity, the difference between p-prims and "conceptions" might be fundamentally one of scale. Could Ohm's p-prim, for example, be understood as a network of resources for understanding agency, effect, and resistance — more effort or less resistance leads to more results? Even the understanding of "more" can be seen to have substructure, as Minksy

(1985) famously illustrated in his account of a "society of more." In this way, Ohm's p-prim could be a cognitive object in the sense of a stable, recurring pattern of activations, the same sense in which a framework theory could be seen as an object at a larger scale.

Wittmann (in press) has proposed "resource graphs" to represent and analyze conceptual change based on a network structure. One challenge in this program is that there are too many degrees of freedom in constructing these graphs. Perhaps it will be useful to experiment with supposing a scale-free pattern — Ohm's p-prim as a highly connected "hub," *force as spinner* as a resource with few connections — as a constraint in the construction of resource graphs. Supposing the network has small-world connectivity might suggest, for example, that hub resources play particular roles in metaphors between physical mechanism and anthropomorphic reasoning (e.g., the system is seeking equilibrium, the puck wants to keep moving).

Of course these are speculations; none of this is to suggest that network theory is the answer. It is to suggest only that it may be a source of ideas, much as computer science has been a source of ideas (including ideas central to diSessa's framework), although it is clear there are limitations in what a computational model can accomplish.

CONCLUSION

It has been almost 30 years since seminal work on students' content area conceptions and conceptual change in physics helped define this as a central focus in physics education research (e.g., Driver & Easley, 1978; Viennot, 1979; Posner et al., 1982). Research in the area has since grown to many thousands of articles and books. As the previous discussion documents, the focus in this research has moved from early metaphors of theory change in science toward a view of students' ideas as emergent, dynamic, and embedded. Such a view helps to integrate a wide variety of findings from apparently conflicting orientations and points toward potentially fruitful future research directions in physics education. We propose the complex systems perspective not as a totally new and original approach, but rather as a perspective that we believe the field has been moving toward and that will prove generative for further development of research, theory, and practice.

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NOTES

1. While this is a fair representation of Vosniadou's published work, recently she has expressed a view that is similar to that expounded here — that presuppositions are themselves entities arising out of the dynamic interactions of smaller components (Vosniadou, 2007, personal communication).
2. We might imagine Ohm's p-prim and up-down organization acting in this way, as effectively permanent features of the system. If they were, one would expect that any reasoning in violation of Ohm's p-prim, for example, such that more effort begets less results, would involve the activation of some other knowledge elements that act to mark the reasoning as exceptional — perhaps to suppress the output of Ohm' p-prim.

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