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An Overview of Conceptual Change Theories

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Conceptual change researchers have made significant progress on two prominent but competing theoretical perspectives regarding knowledge structure coherence. These perspectives can be broadly characterized as (1) knowledge-as-theory perspectives and (2) knowledge-as-elements perspectives. These perspectives can be briefly summarized in terms of the following questions. Is a student's knowledge most accurately represented as a coherent unified framework of theory-like character (e.g., Carey, 1999; Chi, 2005; Ioannides & Vosniadou, 2002; Wellman & Gelman, 1992)? Or is a student's knowledge more aptly considered as an ecology of quasi-independent elements (e.g., Clark, 2006; diSessa, Gillespie, & Esterly, 2004; Harrison, Grayson, & Treagust, 1999; Linn, Eylon, & Davis, 2004)? In this review, we clarify these two theoretical perspectives and discuss the educational implications of each. This debate is important because these perspectives implicate radically different pathways for curricular design to help students reorganize their understandings. Historically, the research literature has predominantly supported knowledge-as-theory perspectives. After outlining both perspectives, this paper discusses arguments and educational implications that potentially favor the adoption of knowledge-as-elements perspectives

Keywords: Conceptual Change, Conceptual Ecology, Knowledge Structure Coherence

INTRODUCTION

Fundamental research among science educators and cognitive scientists focuses on how people learn science and how people apply this knowledge in their daily lives. Theoretical perspectives on knowledge structure coherence are fundamental to much of this research. Researchers have made significant progress on two prominent but competing broad theoretical perspectives regarding knowledge structure coherence: (1) knowledge-as-theory perspectives and (2) knowledge-as-elements perspectives. Essentially, is a student's knowledge most accurately represented as a coherent unified framework of theory-like character (e.g., Carey, 1999; Chi, 2005; Ioannides & Vosniadou, 2002; Wellman & Gelman, 1992)? Or is a student's knowledge more aptly considered as an ecology of quasi-independent elements (e.g., Clark, 2006; diSessa, Gillespie, & Esterly, 2004; Harrison, Grayson, & Treagust, 1999; Linn, Eylon, & Davis, 2004)? Recently, diSessa (2006) organized an excellent review of the historical development in the conceptual change literature along this division. In our review, we clarify the theoretical perspectives and discuss the educational implications of each.

The descriptions of the two theoretical positions presented above are simplifications of the actual perspectives, which are considerably more nuanced as a result of substantial research and ongoing debate amongst their respective proponents. Proponents of knowledge-as-theory perspectives, for example, do not argue that students' knowledge is "theory-like" in the same fashion as the knowledge of scientists (e.g., including the scientists' awareness of the nature of their

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theories or the scientists ability to engage in hypothesis testing with regard to their theories). These proponents do argue, however, for an overarching hierarchical conceptual structure with theory-like properties that constrains a student's interpretation of subordinate models and ideas. Similarly, the knowledge-as-elements perspectives should not be incorrectly caricatured as the random interaction of independent elements. Rather, elements interact with each other in an emergent manner where the combinatorial complexity of the system constrains students' interpretations of phenomenon. While the researchers in each camp also vary along other important issues (e.g., conceptual grain-size, ages of students, methods, and scientific content areas) this debate remains highly visible and contested. The importance of the debate is critical because these models implicate radically different pathways for curricular design to help students reorganize their understandings.

KNOWLEDGE-AS-THEORY PERSPECTIVES

Piagetian learning theory has influenced many researchers of knowledge-as-theory perspectives. Studies of the philosophy and history of science have also influenced many of these researchers. To explain a conceptual shift, proponents of knowledge-as-theory perspectives often present analogies between Piaget's concepts of assimilation and accommodation and Kuhn's (1962) concepts of normal science and scientific revolution (e.g., Carey, 1985, 1999; Wiser & Carey, 1983). While some of these researchers have explained conceptual change in terms of framework theories and mental models (e.g., Vosniadou, 1994; Vosniadou & Brewer, 1992), others have focused on higher level ontological shifts (Chi, 1992). The following section provides an overview of the core conceptual change research related to knowledge-as-theory perspectives.

Research on Conceptual Change by Assimilation and Accommodation

One of the most prominent conceptual change theories, which correspond to Kuhn's notion of a paradigm shift or Piaget's notion of accommodation, was defined by Posner, Strike, Hewson, & Gertzog (1982). They proposed that if a learner's current conception is functional and if the learner can solve problems within the existing conceptual schema, then the learner does not feel a need to change the current conception. Even when the current conception does not successfully solve some problems, the learner may make only moderate changes to his or her conceptions. This is called "conceptual capture" (Hewson, 1981) or "weak restructuring" (Carey, 1985). In such cases, the assimilations go on without any need for accommodation. It is believed that the learner must be dissatisfied with an initial conception in order to abandon it and accept a scientific conception for successful conceptual change. This more radical change is called "conceptual exchange" (Hewson, 1981) or "radical restructuring" (Carey, 1985). According to Posner et al. (1982), the scientific conception must also be intelligible, plausible, and fruitful for successful conceptual change to occur. Intelligible means that the new conception must be clear enough to make sense to the learner. Plausible means the new conception must be seen as plausibly true. Fruitful means the new conception must appear potentially productive to the learner for solving current problems. Posner et al.'s perspective assumes that these cognitive conditions should be met during the learning process for a successful conceptual change. The major goal is to create a cognitive conflict to make a learner dissatisfied with his or her existing conception. Then, the learner may accept a normative view as intelligible, plausible, and fruitful. This view has been very influential theory to determine a learner's specific conceptions that result from the interaction between beliefs and knowledge of the learner.

Posner et al. (1982) embed their explanation of conceptual change within a conceptual ecology perspective. According to Posner et al., a learner's conceptual ecology consists of their conceptions and ideas rooted in their epistemological beliefs. This conceptual ecology perspective has proven very influential. Even though Posner et al.'s primary mechanism for conceptual change has been rejected by many proponents of knowledge-as-elements perspectives, many knowledge-as-elements (as well as many knowledge-as-theory proponents) have adopted this larger conceptual ecology architecture into their perspectives. From a conceptual ecology perspective, the constituent ideas, ontological categories, and epistemological beliefs highly influence a learner's interactions with new ideas and problems. Misconceptions are therefore not only inaccurate beliefs; misconceptions organize and constrain learning in a manner similar to paradigms in science. In other words, prior conceptions are highly resistant to change because concepts are not independent from the cognitive artifacts within a learners' conceptual ecology. Some concepts are attached to others and they generate thoughts and perceptions. Because of this web-based relationship between concepts, a revision to a concept requires revisions to others. Thus, Strike and Posner (1992) advocate that:

> This theory of conceptual change is embedded in a set of epistemological assumptions that are far more generalizable than our application to misconceptions has exploited. These epistemological assumptions suggest that the basic problem of understanding

> cognitive development is to understand how the components of an individual's conceptual ecology interact and develop and how the conceptual ecology interacts with experience (p. 155-156).

Research on the Incommensurability of Adults' and Children's Concepts

Another area of research that supports knowledge-as-theory perspectives focuses on the notion that adults' and children's concepts are each coherent but incommensurable with one another (Carey, 1985). In other words, people maintain coherent theory-like understandings of concepts. Change between concepts can be achieved, according to Carey (1991), through three processes: replacement, differentiation, and coalescence. In replacement, one concept displaces another concept, where the two concepts are fundamentally different; it is an overwrite procedure. Differentiation is another process in which the initial concept splits into two or more new concepts such as dog differentiated into the more specific terms collie and terrier. Coalescence is the opposite process of differentiation; Coalescence involves two or more original concepts coalescing into a single concept, such as collie and terrier into the more general category of dog.

Research on Gradual Transformations of Naïve Theories

While the term "revolutionary" evokes the idea of instantaneous change, recent research supports gradual transformations in conceptual change. Carey (1999) proposes such a view in terms of children's naïve biological theories. She proposes that conceptual change cannot be thought of as "global restructuring" as described by Piaget. Rather, conceptual change should be thought of as "domain specific restructurings." According to this view, children restructure their naïve theory structures by increasing their knowledge in a specific domain. As children are exposed to new experiences and instruction, they gradually replace their theory-like conceptual structures with scientifically correct conceptual structures. These restructurings result from the child's increased knowledge of a domain, social interactions, and a variety of disequilibrating influences, partially resulting from the development of the logical structures of the child.

According to Carey, concepts and beliefs are the two primary components of intuitive knowledge. Beliefs are the relational pieces that connect concepts. For example, "people are animals" refers to two different concepts, people and animals. She argues that while changes in relations between the concepts are relatively easy, changes in the concepts are thorny processes because intuitive theories constrain the concepts in which beliefs are formed. Therefore, conceptual change is a gradual process that occurs at the level of individual concepts.

Hatano and Inagaki (1996) focus on naïve theories of children within biological concepts. Their view is consistent with that of Carey (1999), that young children, before being taught in school, possess a fairly well-developed body of biological knowledge that enables them to make consistent predictions and explanations regarding biological phenomena. Naïve knowledge is constructed through daily experiences at early ages and formal biology is constructed from naïve biology through the restructuring of it.

Research on Mental Models, Framework Theories, and Ontological Shifts

Several researchers focus on conceptual change processes in terms of mental models (e.g., Ioannides & Vosniadou, 2002; Linder, 1993; McCloskey, 1983; Smith, Blakeslee, & Anderson, 1993; Vosniadou, 1994; Vosniadou & Brewer, 1992). Vosniadou and Ioannides (1998), for example, explore spontaneous changes and instruction-based changes at the mental model level. Spontaneous change is change that occurs in young children without specific instruction through the enrichment of observations and other kinds of learning, such as language learning. This position is very similar to Carey's (1999) argument that even very young children develop theories and make predictions about phenomena. Their causal explanations reflect ontological commitments that are subject to revision and radical change. Instruction-based change focuses on the evolution of children's mental models through the introduction of formal scientific instruction. Instruction leads children to construct synthetic mental models that are still inconsistent with the scientific theory. However, these synthetic mental models imply that students begin to synthesize the scientific theory with their initial theory. They make changes in their beliefs based on the instruction of an authority figure, but they still lack the full scientific theory due to their ontological and epistemological commitments.

This development of synthetic models reveals that ontological commitments must be changed in order to fully restructure a student's framework theory. Thus, akin to Carey's opinion, Vosniadou claims that children's generation of scientific models is constrained by their framework theories. For example, elementary school students in Vosniadou and Brewer's (1992) sample consistently constructed the Earth models in disc or rectangular flat shape based on their everyday experience. Vosniadou and Brewer called these "initial" models because they are not affected by the scientific model of the Earth. However, older students constructed some synthetic Earth models (Dual Earth, hollow sphere, and flattened sphere) influenced by the spherical shape of the Earth from instruction. Vosniadou and Brewer suggested that in the formation of these mental models, students' beliefs about the Earth based on their observations and cultural influences are constrained by a naïve framework of presuppositions (Vosniadou, 1994).

> Two of the presuppositions of the framework theory are particularly important because they have the potential to explain the formation of the initial and synthetic models of the Earth children construct. They are: (a) the presupposition that space is organized in terms of the directions of up and down with respect to a flat ground, and (b) the presupposition that unsupported objects fall in a downward direction. The assumption that children are operating under the constraints of these two presuppositions can explain the formation of the initial and synthetic models of the Earth obtained in our sample (p. 55).

According to Vosniadou (1994), students generate misconceptions or synthetic mental models that combine aspects of the scientific model with their initial models within the constraints of their framework theories. The presuppositions of the framework theory need to be revised and eventually replaced to allow for the scientific model.

The framework theory perspective is consistent with Chi's (1992) argument that conceptual change requires an ontological shift. Chi (1992) believes that the conceptual change process is hard because either (a) the student assigns the concept to a different ontological category from the scientific one or (b) the student lacks an appropriate category to which the concept could be assigned. If students become aware of their ontological commitments, they can then become aware of how the scientific theory does not fit with their existing knowledge structure. In turn, they can assign the concept into a correct category by revising their ontological commitments, categories, and presuppositions.

Researchers of these perspectives emphasize that radical changes like these do not take place suddenly. Rather, they involve gradual and time-consuming processes because the student must revise and restructure an entire network of beliefs and presuppositions. While Chi's argument focuses specifically on changing ontological categories, Vosniadou and Ioannides (1998) suggest that ontological change is only one of the changes required in the process of changing theories. As students slowly revise their initial conceptual system over time by adding the elements of scientific explanation, students should be guided through instruction to create larger theoretical constructions with greater explanatory power.

Summary and Synthesis of Knowledge-as-Theory Perspectives

In summary, knowledge-as-theory perspectives hypothesize theory-like naïve knowledge structures. This theory-like knowledge is hypothesized to involve coherent structures grounded in persistent ontological and epistemological commitments. Because novices unconsciously develop these coherent structures through collections of daily experiences, their "theories" are not available for hypothesis testing in a manner similar to scientists' theories. However, novices' alternative conceptions do constrain future learning and allow novices to make consistent predictions across conceptual domains. Knowledge-as-theory perspectives hypothesize revolutionary change in knowledge structures through various mechanisms. Some researchers frame their conceptual change theories in terms of Piaget's notion of assimilation and accommodation or Kuhn's notion of a paradigm shift. Some researchers explain conceptual change in terms of the notion of incommensurability demonstrating the distinction between the roots of the concepts. Other researchers propose ontological shifts and the evolution of mental models. Although these knowledge-as-theory perspectives have developed in different domains, such as force and motion (McCloskey, 1983), astronomy (Vosniadou & Brewer, 1992), biology (Carey, 1999), and heat and temperature (Wiser & Carey, 1983), they all assert that learners at any given time maintain a small number of well-developed coherent naïve theories based on their everyday experiences and that these theories have explanatory power to make consistent predictions and explanations across significant domains.

KNOWLEDGE-AS-ELEMENTS PERSPECTIVES

While the aforementioned knowledge-as-theory perspectives on conceptual change process have wide support within the science education community, several researchers have proposed opposing perspectives that characterize students' understanding in terms of collections of multiple quasi-independent elements (e.g., Brown, 1995; Clark, 2006; diSessa, 1988, 1993; Hunt & Minstrell, 1994; Linn, Eylon, & Davis, 2004). Anderson (1993) and Thagard (1992) provide relatively mechanical/mathematical examples of this perspective. Clark (2006), diSessa, Gillespie, and Esterly (2004), Hunt and Minstrell (1994), and Linn, Eylon, and Davis (2004) maintain more organic perspectives that focus on collections of elements including, but not limited to, phenomenological primitives, facts, facets, narratives, concepts, and mental models at various stages of development and sophistication. diSessa focuses more on the nature of the elements, Clark focuses on longitudinal processes of change, Minstrell focuses on the facets student use in the classroom, and Linn focuses on the process through which students reorganize, revise, and connect these elements. Learning occurs through a process of restructuring and reorganizing these ideas.

diSessa's perspective is the most well known of the knowledge-as-elements perspectives. diSessa (1993) proposes that the knowledge structures of novices consist primarily of unstructured collections of many simple elements that he calls p-prims (phenomenological primitives). P-prims are developed through a sense-of-mechanism that reflects our interactions with the physical world such as pushing, pulling, throwing, and holding. The learner merely assumes that "something happens because that's the way things are" (diSessa, 1993, p. 112). These implicit presuppositions influence learners' reasoning when they interpret the world (Ueno, 1993). P-prims do not have the status of a theory because they are not produced or activated under a highly organized system like the framework theories proposed by knowledge-as-theory perspectives. These p-prims are generated from a learner's experiences, observations, and abstractions of phenomena. Individual p-prims are loosely connected into larger conceptual networks. diSessa describes cuing priority, reliability priority, and structured priorities to propose how those p-prims are recognized and activated according to context.

Some recent empirical evidence supports diSessa's argument. Southerland, Abrams, Cummins, and Anzelmod (2001) explored the nature of students' biological knowledge structure. They concluded that p-prims have more explanatory power than conceptual frameworks theory regarding the shifting nature of students' conceptions of biological phenomena. Clark's (2006) longitudinal study in thermodynamics strongly suggests that students' understanding of heat and temperature can be explained through a related elemental perspective. In the domain of force, Özdemir and Clark (in preparation) investigated knowledge structures of students from kindergarten to high school and found that students' knowledge structures were best described in terms of knowledge-as-elements perspectives.

Summary and Synthesis of Knowledge-as-Elements Perspectives

In summary, knowledge-as-elements perspectives hypothesize that naïve knowledge structures consist of multiple conceptual elements including, but not limited to, phenomenological primitives, facts, facets, narratives, concepts, and mental models at various stages of development and sophistication. Novices spontaneously connect and activate these knowledge pieces according to the relevance of the situation. During the conceptual change process, the elements and interactions between the elements are revised and refined through addition, elimination, and reorganization to strengthen the network. From this perspective, conceptual change involves a piecemeal evolutionary process rather than a broad theory-replacement process.

COMPARISON OF THE TWO VIEWS

There are significant similarities and differences between knowledge-as-theory and knowledge-as-elements perspectives. Table 1 provides a summary of

Table 1. Summary Comparison of Knowledge-as-Elements and Knowledge-as-Theory Perspectives.

Agreements	
Learners acquire knowledge from their daily experiences.	
Learners' naïve knowledge influences their formal learning.	
Much naïve knowledge is highly resistant to change. Thus, conceptual change is a time consuming process.	
Disagreements	
Knowledge-as-Theory Perspectives	**Knowledge-as-Elements Perspectives**
Naïve knowledge is highly organized in theory, schema, or frame forms.	Naïve knowledge is a collection of quasi-independent knowledge elements.
Naïve knowledge in a coherent form has explanatory power to consistently interpret the situations across broad domains.	Consistent application over time for individual contexts, and systematicities will be present, but high contextual sensitivity.
More focus on revolutionary replacement of naïve knowledge in a manner similar to Kuhn's perspectives on paradigms in science. Significant coherence between ideas at any given point in time.	More focus on conceptual change involving evolutionary revision, refinement, and reorganization. Multiple conflicting ideas may coexist simultaneously at any given point in time.
Explanations involve the creation of mental models constrained through the overarching framework theories or ontological categories.	Explanations involve the p-prims and other elements within the learner's conceptual ecology that are most strongly cued by the context.

some of these key similarities and differences. The subsequent sections provide further discussion and clarifications of these agreements and disagreements.

Agreements

Obviously, there are significant areas of agreement and overlap between the two perspectives. We first outline and discuss some of these areas of similarity and later discuss some of the core differences.

Learners acquire knowledge from their daily experiences. Both perspectives agree that novices' conceptual knowledge is heavily influenced by everyday experiences with natural phenomena and events. Therefore, novices' explanations often include scientifically non-normative explanations based on their daily experiences. In order to teach normative scientific theories and concepts, we have to know what students think and then adjust instruction accordingly.

Learners' naïve knowledge influences their formal learning. In addition to influencing their causal explanations, students' prior knowledge influences their formal learning. Students come to formal science instruction with a diverse set of alternative conceptions or misconceptions concerning natural phenomena and events. These alternative conceptions of phenomena and events are often incompatible with scientifically normative ones. Knowledge-as-theory perspectives suggest that if core framework theories can be influenced through instruction, misconceptions will be replaced as changes to the framework theory revision ripple outward through the rest of the connected framework. Knowledge-as-elements perspectives view misconceptions as individual components that require revision and refinement to connect more productively with a more normative conceptual framework. Hence elemental perspectives tend to suggest a bottom-up approach rather than a top-down approach.

Much naïve knowledge is resistant to change. Much naïve knowledge is highly resistant to change by conventional teaching strategies because of its entrenchment in everyday experiences. A number of studies report that students still maintain certain alternative conceptions in spite of substantial instruction.

Disagreements

While there are important similarities in the predictions and expectations of the two perspectives, there are, however, also significant differences between the perspectives. We now outline and discuss some of the most critical differences.

Differences in structural properties of naïve knowledge. The first difference between the two perspectives is about the structure of naïve knowledge. From knowledge-as-theory perspectives, naïve knowledge is highly organized into theory, schema, or frame forms. The root of this theory comes from Piaget's early work and has been strengthened by the similarities between early scientists' knowledge structure and naïve knowledge structure. In other words, knowledge-as-theory perspectives analogize naïve conceptions to naïve theories. On the other hand, knowledge-as-elements perspectives propose that naive knowledge is a collection of quasi-independent simple elements within a larger conceptual ecology that are loosely connected into larger conceptual networks without an overarching structure. Knowledge-as-elements perspectives therefore predict (1) consistent application of ideas over time for individual contexts along with definite systematicities but (2) high contextual sensitivity. Knowledge-as-elements perspectives also predict that individuals may simultaneously maintain multiple conflicting ideas on a regular basis.

Dispute about consistency vs. inconsistency. Another difference between the two perspectives focuses on the domain size across which a novice's predictions and explanations should be consistent. According to knowledge-as-theory perspectives, fundamental presuppositions, ontological and epistemological commitments, (e.g., heavy objects fall faster) are embedded in naïve theories and students explanations are constrained by them. Therefore, a naïve theory guides a novice to make consistent predictions and causal explanations across multiple contexts spanning broad domains (that may or may not parallel the domains of related normative concepts). Furthermore, there should be much coherence between ideas. On the other hand, from knowledge-as-elements perspectives, novices' knowledge structures are much more contextually sensitive. A novice's predictions or explanations will be consistent for specific related contexts over time, but this consistency doesn't extend across broad domains because of the contextual sensitivity of the constituent elements and cuing relationships. Therefore, while there will be local systematicities in novices' predictions and explanations, knowledge-as-elements perspectives suggest that novices' will not demonstrate consistency across broad domains.

Revolutionary vs. Evolutionary change. A third important difference between the perspectives focuses on the nature of change processes. Knowledge-as-theory perspectives often suggest revolutionary change where current concepts are abandoned and replaced with normative concepts. According to knowledge-as-theory perspectives, novices already have extensive well-defined theoretical structure from the beginning. Novices need to add new knowledge elements into the existing conceptual structure and/or modify the existing knowledge elements of their conceptual structure in order to replace their initial theory with the scientific one. The change is basically defined as holistic and dramatic, although many theorists acknowledge that the process is often time consuming and lengthy. The important idea is that revolutionary change occurs between distinct understandings or models that are theory-like in character. Thus, there should be significant coherence between ideas at any point along the change process.

Knowledge-as-elements perspectives propose a more evolutionary trajectory without such distinct phases or stages. Learning involves the gradual accretion and piecemeal eliminations, additions, and organization of elemental knowledge pieces where multiple contradictory ideas can coexist within a student's conceptual ecology. Knowledge-as-elements perspectives suggest that the knowledge-forming process begins with quasi-independent small knowledge elements that get connected to create more complex (hopefully more normative) conceptual structures by adding new knowledge elements, reorganizing connections, and/or modifying existing simple knowledge elements through an evolutionary process. This contrasts with knowledge-as-theory perspectives that suggest revolutionary processes of conceptual change where one theory-like understanding is replaced by another theory-like understanding.

Empirical Evidence for Conceptual Change Theories

Historically, the research literature has predominantly leaned toward knowledge-as-theory perspectives (diSessa, 2006; Driver, 1989). We now discuss arguments and educational implications that potentially support the adoption of knowledge-as-elements perspectives. In particular, we now present some recent research findings on knowledge structure coherence that lead us to lean toward the knowledge-as-elements perspective. First we discuss a series of studies and replication studies by Ioannides and Vosniadou (2002), diSessa, Gillespie, and Esterly (2004), and Özdemir and Clark (in preparation). We then present data from several other related studies.

Ioannides and Vosniadou (2002) investigated the meaning of force and its development among 105 children across four age levels. What they found was that 88.6% of the subjects' responses fell into seven categories of internally consistent interpretations of force. The seven categories include: (a) internal force, (b) internal force affected by movement, (c) internal and acquired force, (d) acquired force, (e) acquired force and force of push/pull, (f) force of push/pull, and (g) gravitational and other forces. For example, a student with internal force meanings always explained that force is related to an objects' size or weight. The students in this study thus made consistent predictions and gave consistent explanations regardless of context. Therefore, the Ioannides and Vosniadou concluded the students' interpretations of force were uniform and internally consistent.

diSessa et al. (2004) conducted a quasi-replication and extension of the Ioannides and Vosniadou study. diSessa et al. found that students' meaning of force could not be explained by the coherence claim. Students' responses were inconsistent across contexts, even in the replication part of the study. The results of the study also support several alternative explanations in which the learner's understanding of force is context-dependent. The findings supported earlier work suggesting that naïve knowledge consists of unstructured small pieces that are unconsciously activated in certain circumstances (diSessa, 1993). Indeed, even the color of an object could affect the explanations of kindergarten students in responding the questions of force.

The conflicting findings between the Ioannides and Vosniadou (2002) study and diSessa et al.'s quasi-replication (2004) suggested the need for further clarification. Recently, Özdemir and Clark (in preparation) conducted a replication study with four age groups of Turkish students to resolve the coherence vs. fragmentation dispute about students' understanding of force. The study applied the coding schemes based on both Ioannides and Vosniadou (2002) and diSessa et al. (2004). The results of the study suggest that students' interpretation of force supports knowledge-as-elements perspectives overall. The results of this study also indicate that methodological flaws such as employing soft coding schemes and assessing students' understanding of force in limited number of contexts can overestimate students' knowledge coherence. Even small contextual variations may affect students' interpretations of force and, thus, this causes fragmentation in their causal responses.

In addition to this series of replications and quasi-replications, several other recent studies investigating the debate have provided further support for knowledge-as-elements perspectives. First among these, Southerland, Abrams, Cummins, and Anzelmod (2001) explored the nature of students' biological knowledge structure. They concluded that p-prims have more explanatory power than conceptual frameworks theory regarding the shifting nature of students' conceptions of biological phenomena. Second, diSessa, Elby, and Hammer (2002) documented contradictory claims and explanations for the same situation in different occasions in the domain of force and motion. Third, Thaden-Koach, Dufresne, and Mestre (2006) investigated fifty college students' understanding about moving objects by using coordination class theory (diSessa & Sherin, 1998). The result of the study highlights the contextual sensitivity. Thus, they concluded that " …learning in a domain like physics is a complex endeavor requiring considerable time, instructional resources, and appreciation of the complexity of applying ideas across diverse contexts (p. 10)." Fourth, Wagner's (2006) case study analysis suggests that students' conceptual understanding is often highly context sensitive and that transfer therefore requires the acquisition of abstract representations by means of "the incremental refinement of knowledge resources that account for-rather than overlook-contextual variation (p.1)." Finally, Clark's (2006) longitudinal study in thermodynamics showed that students' explanations evidenced multiple contradictory ideas, disruptive experientially supported ideas, difficulties productively connecting normative ideas, and the active pursuit of idiosyncratic explanations. That study demonstrates that "students' understanding of thermal equilibrium evolve from disjointed sets of context-dependent ideas toward, if not achieving, integration, normatively, and cohesiveness (p. 467)."

Therefore, although researchers are still debating this issue and there is not yet consensus on knowledge structure coherence and the mechanisms of conceptual change, our view aligns more closely with the knowledge-as-elements perspective because of the results of these recent studies.

IMPLICATIONS FOR INSTRUCTION

The implications of these disputes for instruction are profound. Determining whether students' intuitive knowledge consists of many quasi-independent elements, as suggested by knowledge-as-elements perspectives, or of a network of theories, as suggested by knowledge-as-theory perspectives, is critical; it affects our understanding of the conceptual change process, curriculum design, and instructional strategies. If a learner's understanding is theory-like, and if certain specific conditions are met, the learner will become dissatisfied with existing conceptions when conflicting examples are introduced to the learner (Strike & Posner, 1982). It is believed that such conceptual conflict could make the learner abandon existing misconceptions and accept scientifically appropriate alternatives if the learner could not otherwise dismiss, ignore, or reinterpret them within the existing framework (Chinn & Brewer, 1993). On the other hand, if a learner's intuitive knowledge is elemental in nature, instruction should focus on how those elements are activated in appropriate contexts. Teachers may first make students aware of their central pieces of knowledge and then allow students to use them in appropriate contexts. From this perspective, productive curriculum design might confront students with the same phenomena in different contexts. The curriculum would therefore focus more on a refinement processes including addition, modification, elimination, and organization of the knowledge elements in learner's knowledge structure over time.

From a constructivist view, all of the various elements in a student's conceptual network are subject to progressive knowledge construction. School science often conflicts with students' intuitive knowledge. If we merely target students' misconceptions with replacement procedure as suggested by radical revolutionary models, we might only achieve these replacements in a limited number of contexts which might remain independent of students' interpretations of experiences outside of the classroom. Therefore we should attempt to help students reorganize and reprioritize the elements and connections of their conceptual network if we want to allow students to construct a scientific theory that is applicable to a number of situations. This cognitive process cannot be achieved by interpreting students' knowledge structures with small number of mental representations or conceptual schemes.

Because constructivism sees students' existing ideas as a primary source for learning, erasing misconceptions with a replacement model is at odds with this paradigm. In their paper, Smith, diSessa, and Roschelle (1993) extensively discuss how traditional view on misconceptions and the process of conceptual change are at odds with constructivism:

> Our central claim is that many of the assertions of misconceptions research are inconsistent with constructivism. Misconceptions research has emphasized the flawed results of student learning. Constructivism, in contrast, characterizes the process of learning as the gradual recrafting of existing knowledge that, despite many intermediate difficulties, is eventually successful. It is difficult to see how misconceptions that (a) interfere with learning (b) must be replaced, and (c) resist instruction can also play role of useful prior knowledge that supports students' learning. If we take constructivism seriously, we must either reconsider the solely mistaken character of misconceptions or look for other ideas to serve as productive resources for student learning (p.123-124).

When we look at conceptual change from diSessa's epistemological stance, we should attempt to help students reorganize and reprioritize the elements and connections of their conceptual network. P-prims such as force as mover, dying away and spontaneous resistance describe the events in the physical world in terms of intuitive conceptualization (diSessa, 1993). The idea is that these p-prims should be cued in several appropriate contexts to build more complex and stable formal knowledge. In this case, p-prims within the students' alternative conceptions take a function to serve as productive tools for expertise. For example, the function of the dying away conception can be invoked as part of formal concepts and learning (diSessa, 2006). In a simple event, tossing a ball into the air, students naturally recognize that the motion of the ball eventually dies away. This knowledge element is often self explanatory in the sense that there is no need to explain the cause of the event. However, if the causality behind a novice's explanation is investigated, the novice most probably raises the concept of gravity. Novices might say that the upward force on the ball is decreased by gravity until a balance occurs between the upward force and gravity at the peak in the air. Although this causality is non-normative, it provides extremely useful building blocks for the process of refining a student's understanding of the concept of conservation of energy and the concept of momentum in science.

In terms of specific instructional strategies, knowledge-as-elements perspectives suggest that conceptual change requires restructuring, editing, and organizing rather than discrete changes from one conception to another especially for complex and rich domains such as mechanics and thermodynamics. Toward this goal, engaging students with multiple computational representations suggests great promise for instruction. More specifically, instruction engaging multiple representations can re-represent concepts in multiple ways to highlight specific variables within each context separately while ignoring the others (Ainsworth, 1999). The complexity of a phenomenon can be simplified to help a learner focus on the specific aspects of the phenomenon across multiple contexts. Parnafes (submitted) investigated students' learning processes about physical phenomena through computational representation. Her research was grounded upon a knowledge-as-elements perspective. Her analyses suggested that (1) instruction engaging multiple representations can highlight the important aspects of phenomena so that a learner can easily see and differentiate between them, (2) instruction engaging multiple representations can help students identify fragmentation in their causal responses and encourage students to engage in conflict resolution and coherence-building between ideas, and (3) instruction engaging multiple computational representations can provide interactive visual aids for the investigation of phenomena. Therefore, while multiple instructional strategies can offer synergistic benefits, instruction engaging multiple computational representations seems particularly powerful from knowledge-as-elements perspectives.

FINAL THOUGHTS

In our review, we have outlined key features of knowledge-as-elements and knowledge-as-theory perspectives. There is likely no single truth to explain the complex processes of conceptual change and naïve knowledge structure. One possibility is that the degree of the richness of a scientific domain might be an indicator to decide which theory is more useful for describing and analyzing conceptual change. For example, diSessa developed his knowledge-as-elements perspectives for the rich domain of mechanics while Vosniadou's knowledge-as-theory perspectives were developed in domains with which students have less first-hand interaction (e.g., astronomy).

A key issue to consider is that students' learning processes and trajectories may involve periods and aspects of both coherence and transition. Fewer and fewer researchers currently espouse radical knowledge-as-theory perspectives. Wiser and Amin (2001) for example suggest that conceptual change involves both revolutionary as well as evolutionary components. Similarly, Susan Carey suggests that both strong and weak restructuring occurs and that the process takes time. Stella Vosniadou also agrees that the process takes time and that students may temporarily embrace multiple "synthetic models" between stages. At the same time, diSessa and others are currently working on research about coordination classes to explain systematicities and connections between ideas rather than focusing predominantly on the quasi-independence of the various elements. There is therefore a convergence toward the center of these perspectives in order to account for coherence, systematicity, and transition.

Ultimately, knowledge-as-elements perspectives may prove most useful because they provide more tools with which to interpret times of transition in students' understanding even if students' initial understandings (and even intermediate stages) are indeed theory-like in nature. The knowledge-as-theory perspectives discussed above acknowledge that conceptual change may take extended periods of time, but they generally provide less detail about the mechanisms for these transitions. Tools for explaining and modeling transitional times are critical, because these transitional times may extend across many school grades and on into adulthood. Therefore, although there are strong arguments from knowledge-as-theory perspectives regarding the theory-like understandings of young children, for example in terms of a naïve biology (e.g., Inagaki & Hatano, 2002; Carey, 1999) or even astronomy (e.g., Vosniadou & Brewer, 1994), the arguments are much less strong for older students. Ioannides and Vosniadou (2002) for example, present data that is compelling regarding the coherence of younger students' understanding about the concept of force, but that study presents less compelling data regarding the coherence of older students' understandings, which can only be grouped into a catch-all category of "gravity and other." Older students' understandings therefore seem much more transitional and fragmented. This transition has been shown to extend well into adulthood, if not permanently. Clarks' (2006) longitudinal study of students understanding of thermodynamics tracked students from eighth grade through twelfth grade and showed ongoing transition across these years. Therefore, even if for the sake of argument we accept that young students' exhibit naïve knowledge with theory-like attributes, the strongest argument for knowledge-as-elements perspectives may be that it can account both for coherent phases as well as transitional phases while knowledge-as theory-perspectives focus primarily on phases of the process that appear much more ephemeral after the early years.

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