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Perspectives on Conceptual Change

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Scientific Explanation, Systematicity, and Conceptual Change

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Introduction

Humans possess remarkably rich and adaptive conceptual knowledge systems that enable them to form relatively stable representations about the world, perceive coherence amidst noise and chaos, and communicate elaborate explanations to others who see the world in strikingly similar ways. On the other hand, knowledge can sometimes be surprisingly brittle and context-bound, coherence may be more illusory than real, and individuals (e.g., teachers and students) may repeatedly fail to achieve common ground during routine discourse. How can we account for such apparent contradictions? Conceptual change names a family of theories, methodological approaches, and research traditions concerned with the origin, ontogenesis, and evolution of knowledge systems as a result of formal and informal learning. Conceptual change is the subject of considerable research across all of the cognitive sciences. In particular, it is central to investigations in the philosophy of science, cognitive development, and science education.

The speakers in this symposium will address issues in conceptual changes as they pertain to children, students learning science, lay adults, and practicing scientists. They will consider philosophical, developmental, computational, and instructional issues related to the characterization of systematicity and coherence in scientific explanation. The participants will offer distinct and sometimes divergent points of view on conceptual change with particular attention to the reasons and mechanisms that produce systematicity and coherence (and alternatively incoherence) within and across individuals in generating scientific explanations. The speakers will address a range of related questions, including the following:

1. How can we characterize the state of knowledge structures prior to formal learning? What happens to students' knowledge when it makes contact with formal learning?
2. What are the knowledge elements that undergo change in conceptual change (e.g., beliefs, theories, schemata, propositions, and coordination classes)? What constitutes evidence for such changes?
3. What are "common" or "typical" trajectories in conceptual development (e.g., from atheoretical to theoretical, incoherent to increasingly coherent)? How can we account for periods of stability and instability in the generation of scientific explanations?
4. What are the mechanisms of change (e.g., differentiation, belief revision, enrichment, conceptual combination, re-organization and reprioritization of knowledge elements)?

5. What factors or criteria contribute to the acceptability, plausibility, and overall appraisal of scientific explanations in children, lay people, and scientists?
6. How can we expand the scope of conceptual change research to incorporate emotional and motivational variables?

Research in the philosophy of science, cognitive development, and science learning has several interesting points of convergence, despite the fact that they constitute different research programs. Philosophy of science is a discipline devoted to analyzing the character of scientific investigations (Bechtel, 1988). It endeavors to answer questions such as what constitutes a valid scientific explanation and how do scientific theories change over time. Conceptual development research is devoted to the study of age-related transitions in domain-specific (e.g., physics, biology) understandings. Conceptual change investigations in science education focus on a) characterizing transformations in learners that (with varying success) result in transformations in understanding of scientific phenomena and b) promoting instructional situations that increase the likelihood of robust and generative understanding.

Each of these disciplines is focally concerned with changes in knowledge systems that go well beyond mere knowledge accretion or belief revision. There is general agreement that conceptual change necessitates a substantial reorganization of knowledge. The history and philosophy of science (HPS) has had an enormous influence on both cognitive development and science education research (Brewer, Chinn, & Samarapungavan, 1998). HPS has provided an explanatory vocabulary for characterizing changes in scientific understanding and criteria for evaluating the quality of explanations. It has also served to highlight the fundamental commonalties underlying the conceptual change process and has led to some strong claims about the deep structural similarities between children (or naïve students) and practicing scientists. Clearly, not every theorist views the "scientist as child" metaphor as equally illuminating. In fact, each of the participants in this symposium has been critical of this perspective. Nevertheless, this point of view serves to introduce some important distinctions about the "theoretical character" of conceptual learning.

Theory theory proponents claim that there are deep similarities between scientists and children in the formation of theories (e.g., Gopnik & Welllman, 1994). Children's naive theories embody causal notions, enable distinct types of interpretations, explanations, and predictions, and are similarly subject to processes of modification and revision as the evidence dictates. The process of conceptual change in children is very similar in character to the process of theory revision in science. Vosniadou (1994) views conceptual change in children and science students as differing substantially in character from scientific theory change in that children lack systematicity, abstractness, and metaconceptual awareness (i.e., understanding the hypothetical nature of their beliefs). She proposes the notion of framework theories, which consists of basic presuppositions about the way the world works and serves to constrain the acquisition of science concepts. These framework theories guide children's interpretation of scientific phenomena and enable them to generate scientific explanations and predictions in a reasonably consistent fashion (Ioannides & Vosniadou, submitted). These "theories" are continuously enriched, differentiated, and revised as children encounter new information. However, when framework theories come into contact with formal science instruction, fragmentation, incoherencies, and misconceptions are often the result.

diSessa (1993) begins with the premise that naïve understandings of the physical world constitute a rich, complex, and diverse knowledge system. However, the system as a whole is only weakly organized and students' intuitive scientific understandings are often a fragmented, loosely connected, collection of ideas, having none of the commitment or systematicity attributable to theories. The elements of knowledge called "p-prims" reflect minimal abstractions from common experience. Through learning and instruction, p-prims get tuned to newer contexts, refined, and reprioritized as the knowledge system is reorganized. They become supplanted in many contexts by more complex explicit knowledge structures that include physical laws. However, p-prims continue to exert substantial influence even in the reasoning of experts. Growth in scientific understanding involves a major structural change toward systematicity. Recently, diSessa and Sherin (1998) introduced the notion of coordination class, which involve systematically connected ways of gaining information from the world. Coordination classes include strategies of selective attention and systematic integration of observations.

In characterizing the nature of change in the history of science, Thagard (1992) identifies degrees of conceptual reorganization, ranging from belief revision to wholesale changes in the organizing principles underlying a conceptual system. For example, Darwin's theory of natural selection redefined the classification of organisms according to historical lineage rather than feature similarity. The theory of explanatory coherence (instantiated in a connectionist model, ECHO) is integral to understanding the differential evaluation of competing hypotheses for best explanation and more generally, the process of conceptual change/theory adoption in science. The theory provides a set of principles (e.g., symmetry, simplicity, and data priority) that establish relations of coherence and incoherence between propositions. Thagard has used the theory of explanatory coherence, as instantiated in ECHO, to model numerous theoretical disputes in the history of science. Thagard (1992) also considered whether conceptual change is similar in scientists and children. His analysis of the kinds of epistemic changes and process of “theory revision” reported in the developmental literature suggests that they are not typically characteristic of the kinds of dramatic changes evidenced in scientific conceptual revolutions. Thagard has also considered how other forms of coherence such as analogical, deliberative, and most recently, emotional coherence affect argumentation and theory change (in press).

Conceptual Change in Science Learning: From Coherence to Fragmentation

Stella Vosniadou

Accounts of the knowledge acquisition process have customarily assumed that knowledge acquisition proceeds in a continuous manner enriching initially fragmented conceptual structures and making them increasingly more systematic, and more coherent. In this paper I will try to develop a different point of view based on a series of empirical studies investigating the development of science concepts. More specifically, the following arguments will be made with respect to a) the nature of children’s initial conceptual structures and b) the process of conceptual change.

Initial conceptual structures: There is considerable agreement in the cognitive science and science education literature that by the time children go to school they have acquired considerable knowledge about the physical world (an intuitive physics) that exerts considerable influence on subsequent learning and particularly on learning science. Researchers disagree, however, on the exact nature of such an intuitive physics. One view, expressed by diSessa (1988) is that initial knowledge structures about the physical world consist of an unstructured collection of small knowledge elements, which he calls phenomenological primitives (p-prims). These pieces of knowledge are generated as abstractions of common phenomena and are activated in certain characteristic cases. According to this view the process of conceptual change is one of collecting and systematizing the fragments of knowledge into consistent wholes. This happens as p-prims change their function in order to be integrated into the scientific framework.

Unlike the above view of knowledge acquisition, a number of empirical studies investigating the process of knowledge acquisition in science conducted in our lab, show that preschool children answer questions about force, matter, heat, the earth, etc., in a relatively consistent way, revealing the operation of a common explanatory framework (Vosniadou & Brewer, 1992; 1994; Ioannides & Vosniadou, 1991; submitted). These results are consistent with research on conceptual development in infancy showing that the process of knowledge acquisition starts immediately after birth and proceeds in an orderly fashion towards the construction of an initial framework theory of physics that allows children to function adequately in the physical environment. The term theory is used here to denote a causal, relational explanatory structure and not an explicit, well formed and socially shared scientific theory. In other words, the empirical results support the hypothesis that children’s initial conceptual structures are not as fragmented as initially thought, but rather, children start the knowledge acquisition process by forming rather narrow but nevertheless internally consistent explanatory frameworks.

The process of conceptual change: The results of the empirical studies mentioned above show that the process of conceptual change is a slow and gradual affair that happens over a long period of time. During this process, we do not observe a change from fragmentation to increased coherence. Rather, the initial explanatory structures become more fragmented as aspects of the scientific theory are assimilated into the framework theory either creating synthetic models (which are internally consistent but scientifically wrong) or internally inconsistent structures.

In order to better understand the debate regarding coherence vs. fragmentation we should take into consideration the fact that most of the studies that support the argument that knowledge of physics’ concepts consists of “disconnected knowledge fragments” (see also Reif & Allen, 1989), are studies of older students (either college students or late high school students). On the contrary the arguments that support the coherence to fragmentation view (e.g., Vosniadou, 1994) are based on experimental evidence coming from younger children. The argument advanced here is that both of the experimental findings are correct, but that the fragmentation observed in older children and naïve adults represents a change from initial coherence to fragmentation. This is the case because a) initial conceptual structures are much more cohesive that originally thought, and b) because science instruction proceeds by fragmenting initial explanatory frameworks without succeeding in building an alternative cohesive scientific explanatory framework. Although increased fragmentation appears to be the common result of much science instruction, the process of knowledge acquisition does not stop there. The students that proceed to become experts acquire increasingly less fragmented and more cohesive science concepts.

A Complex Adaptive Systems View of Conceptual Change

Andrea A. diSessa

Although it seems largely unacknowledged in the conceptual change community, there is a huge diversity of views about basic issues in conceptual change. Even the seemingly innocuous question "what changes in conceptual change (and what does not)?" leads to a plethora of views invoking not obviously commensurable explanatory constructs such as concepts, beliefs, models, ontologies, ontological commitments, nodes and links, schemata, and so on. One of the major fault lines in the community concerns whether conceptual change is *localizable* (e.g., in a few discrete entities, such as concepts), or whether, in contrast, it is more appropriate to think of conceptual change as emergent within a *complex system*, implicating many types of mental entities and many possible configurations. Localizability will be the focal issue of this talk.

I propose to explain and advocate the "complex adaptive systems view" (CASV) of conceptual change beginning by motivating the CASV approach methodologically. If we are to settle issues such as the localizability of conceptual change, it is imperative that we announce and debate standards for explanation within this research area. I put forward a beginning set of standards:

- Theoretical accountability — Accounts of conceptual change should employ technically well-developed explanatory constructs (e.g., concept, ontology, etc.). Dictionary definitions don't come close to the level of specificity one needs in scientific accounts of cognitive development. At a minimum, an appropriately developed explanatory construct should allow distinguishing, in principle, between instances and non-instances of such a construct. One should expect, sooner or later, that accounts of such constructs include specification of the processes of normal deployment the construct and processes of change.

- Empirical accountability — Although a wide range of empirical methods are appropriate for studying conceptual change, we may still hold some general principles. In particular: (a) we should expect empirical work to include, in some measure, process data that can confirm or disconfirm assumptions about theoretical entities and processes hypothesized to be involved in conceptual use and conceptual change; (b) we should expect sufficient breadth of experimentation to allow limits of contextual dependence of both the construct involved and particular instances of the construct. Both (a) and (b) are plausible general accountabilities. The vast majority of conceptual change studies collect no process data, and (b), *contextuality*, is particularly important in settling localizability questions.

I will exemplify these principles in two ways: First, I will introduce some particulars of my own CASV approach, including (a) two claimed-to-be well-rationalized explanatory constructs, *p-prims* (diSessa, 1993) and *coordination classes* (diSessa & Sherin, 1998), and (b) examples of process and other data that support theoretical claims and entailments. P-prims constitute a large class of simple "intuitive" schemata, and most directly limit claims of localizability in conceptual change. A coordination class is a model of a large-scale knowledge system constituting (a step toward) a technically precise and cogent definition of a particular class of concepts. Coordination classes define a number of obvious partial constructions of a full "concept," which, once again, provides opportunities to examine localizability of conceptual development empirically.

Finally, I will enter into an abbreviated "competitive argumentation" comparing the success of this version of CASV with excellent recent work by Vosniadou and Ioannides (Ioannides & Vosniadou, submitted) studying the same conceptual terrain, mechanics—work that is, however, open to criticisms on the basis of the above principles. In particular, we have recently begun to gather and analyze data to bridge age-of-subjects and other methodological differences that has, so far, kept comparisons from being as compelling as they might be. We are gathering data over the same age ranges as Vosniadou and Ioannides, using similar methods, but with a slightly more open protocol to allow better contextuality analysis and some relevant process data. By the time of the conference, we should have preliminary results that bear directly on the cogency of Vosniadou's theoretical frame, and, in particular, on the localizability of conceptual change concerning the concept "force."

Emotional Coherence in Scientific Explanation and Conceptual Change

Paul Thagard

Scientists are supposed to be dispassionately rational, but they are as emotional as other people. Theories are not only accepted or rejected: sometimes they are loved or hated. Good theories are often praised for their beauty and elegance, while bad theories are sometimes derided as ugly or crazy. This talk will interpret the cognitive-emotional judgments of scientists in terms of a recently developed theory of emotional coherence (Thagard, in press). My earlier work used a computational model of explanatory coherence to explain the acceptance and rejection of hypotheses on the basis of the degree to which they satisfy a set of constraints defined in terms of explanation and evidence (Thagard, 1992). In line with much recent research in psychology and neuroscience on the ubiquity of emotions in cognition, my new model incorporates emotion into coherence computations and shows how emotional judgments can emerge from explanatory and other kinds of inference. The diversity and intensity of reactions to controversial theories such as evolution by natural selection can be explained by the theory of emotional coherence. Theory change is in part a matter of emotional change, as scientists shift their emotional attitudes toward hypotheses from positive to negative and vice versa. For example, in recent years most gastroenterologists have shifted their attitudes concerning the bacterial theory of ulcers from feeling it was ridiculous to viewing it as powerful and exciting (Thagard, 1999).

Conceptual change is also an emotional as well as a cognitive process. Concepts are mental representations corresponding to words, whereas propositions are mental representations corresponding to sentences. Both kinds of mental representations usually have emotional valences attached to them. For example, the valence of "baby" is typically positive, and the valence of "garbage" is typically negative. Conceptual change is emotional change when it involves a shift in valence from positive to negative or vice versa. In the Darwinian revolution, for example, many people shifted the valence attached to "evolution" from negative to positive. I will describe how the theory of emotional coherence can account for this aspect of conceptual change.

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