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Conceptual change

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Introduction

Much of the attention of philosophy of science, history of science, and psychology in the twentieth century has focused on the nature of conceptual change. Conceptual change in science has occupied pride of place in these disciplines, as either the subject of inquiry or the source of ideas about the nature of conceptual change in other domains. There have been numerous conceptual changes in the history of science, some more radical than others. One of the most radical was *the chemical revolution*. In the seventeenth century, chemists believed that the processes of combustion and calcination involved the absorption or release of a substance called *phlogiston*. On this theory, when an ore is heated with charcoal, it absorbs phlogiston to produce a metal; when a metal is burned, it releases phlogiston and leaves behind a residue, or *calx*. The concept of phlogiston derived from a quite complex Aristotelian/medieval structure that included three concepts central to chemical theory: *sulphur*, the principle of inflammability; *mercury*, the principle of fluidity; and *salt*, the principle of inertness. All material substances were believed to contain these three principles in the form of *earths*. The phlogiston theory held that in combustion, the sulphurous earth (phlogiston) returns to the substance from which it escaped during some earlier burning process in its history, and that in calcination the process is reversed. However, chemists also knew that a calx is heavier than the metal from which it was derived. So, the theory implies that phlogiston has a negative weight, or a *positive lightness*. This did not present a problem, though, because it was compatible with the Aristotelian *elements* of fire and air (the others being earth and water), which were not attracted towards the center of the earth. The development of the oxygen theory of combustion and calcination by Lavoisier in the late eighteenth century has been called *the chemical revolution* because it required replacing the whole conceptual structure with, for example, different concepts of *substance* and *element* and new concepts of *oxygen* and *caloric*. In the new system, it was no longer possible to believe in the existence of substances with negative weight. According to the oxygen theory, oxygen *gas* is released in combustion and absorbed in calcination. Thus *calx* is metal (substance) plus oxygen, rather than metal minus phlogiston. The concept of phlogiston was eliminated from the chemical lexicon. The reconceptualization of chemical phenomena that took place in the chemical revolution made possible the atomic theory of matter, which, as we know, posits quite different constituents of material substances from the *principles* central to the earlier conceptual structure. Just what constitutes *conceptual change*, how it relates to theory change, and how it relates to changes in belief continues to be a subject of much debate. Clearly, though, as the preceding example demonstrates, the three are significantly interrelated.

There has been considerable mutual influence among the disciplines of philosophy of science, history of science, and psychology as regards research on the topic of conceptual change. With the development of the interdisciplinary field of cognitive science, that influence has been transformed into a deliberate use of research across a subset of practitioners of these disciplines. The future in this area, as in the field of cognitive science generally, lies in the synthesis of research in the different disciplines and in collaborations among them. In this discussion we will focus on the three most interactive areas that address conceptual change: cognitive development, science learning, and scientific change. In each of these areas there is considerable debate as to what constitutes conceptual change and how significant it is to understanding development, learning, and science, respectively. The objective of this chapter is to provide some insight into the issues and research of those who contend that conceptual change plays a major role in human cognition and to weave some connecting threads among them.

Briefly, how does the problem of conceptual change arise in each of these areas? In the area of cognitive development, the pioneering work of Jean Piaget found that children have concepts that are significantly different from those of adults and argued that a child's concepts change over the developmental process. Much contemporary research into children's intuitive understandings across a wide range of phenomena, including the shape of the earth, the day/night cycle, living things, and mental states, supports and extends at least the broad outlines of Piaget's findings. From this perspective, then, understanding cognitive development and its relation to maturation requires addressing the nature and processes of conceptual change (see Article 6, COGNITIVE AND LINGUISTIC DEVELOPMENT).

In the area of science learning, especially with the development of the field of *cognition and instruction* in the late 1970s, considerable research has established that students are not blank slates on which teachers can imprint scientific knowledge. Students come to school with intuitive conceptualizations of physical phenomena in several domains which differ from those of science. Further, these intuitive conceptualizations prove to be highly resistant to instruction. Developing pedagogical strategies to facilitate the shift from intuitive to scientific understanding requires insight into the nature and processes of conceptual change (see Article 54, EDUCATION).

Finally, in the area of scientific change, the histories of the various sciences exhibit considerable conceptual innovation and change. In some cases, such as the advent of relativity and quantum mechanics early in this century, the change in the conceptualization of nature has been so radical as to warrant the designation of a "revolution." Even though revolutionary conceptual change is infrequent, creating concepts through which to understand, structure, and communicate about physical phenomena occupies a central position in the scientific enterprise. Explaining scientific change requires examining how new conceptual structures emerge in science, what relation they bear to existing structures, and how they come to replace these. Most of our discussion will focus on scientific change, because research by philosophers and historians of science, to date, has had more impact on the areas of cognitive development and science learning than the reverse (see Article 60, SCIENCE). However, thinking about conceptual change in contemporary philosophy and history of science has been influenced considerably by other areas of cognitive science described in this volume.

Scientific change

Addressing the problem of conceptual change is essential to understanding the nature and development of scientific knowledge. The major changes in physical theory at the turn of the twentieth century thrust the problem of conceptual change into the spotlight for philosophers and historians of science. For nearly 300 years Newtonian mechanics had been held to be a true theory, and change within physics was seen largely as elaborating and extending the Newtonian world view. Characterizing conceptual change in such a way as to reconcile the seemingly radical reconceptualizations offered by relativity and quantum mechanics with an understanding of scientific change as by accretion shaped the initial perception of the problem in this century.

Until the advent of cognitive science, the two most influential views on conceptual change in science were the *received* view associated with logical positivist philosophers, chief among them Rudolph Carnap, Hans Reichenbach, and Carl Hempel, and the *radical* view of certain historicist philosophers, Norwood Hanson, Paul Feyerabend, and Thomas Kuhn. For the first half of the century, the characterization of the logical positivists held sway. They were called *positivists* because they identified with the tradition, originating with August Comte in the early nineteenth century, that held science to be the paradigm of empirical knowledge. In Comte's own view, science was the final, *positive* stage in the history of humankind's attempt to understand nature. The *logical* came from their advocacy of the newly developed symbolic logic as the primary methodological tool for analyzing scientific knowledge. The logical positivists approached the problem of conceptual change as follows. First, they characterized conceptual change as *continuous and cumulative*, holding the new conceptual structures to be logical extensions of previous ones. Second, they viewed scientific conceptual structures as languages and explored the relation of the terms (scientific concepts) in these languages to empirical phenomena and to one another using the methodological tools afforded by logic.

Beginning in the 1960s, the historicist philosophers offered critiques of positivism from the perspective that understanding scientific change requires reference to the actual history of science. The *radical* contingent argued that science history shows that major changes are best characterized as revolutions, in that they involve overthrow and replacement of the reigning conceptual system with one that is, at the very least, logically inconsistent with it, and at worst, what they called *incommensurable* with it. To take one of the stock examples, *mass* in Newtonian mechanics is an invariant quantity, whereas *mass* in relativity theory varies with motion. Though the same term is used in both cases, the meanings are so different that the relativistic conceptual structure cannot simply incorporate or *translate* the Newtonian structure within its bounds but replaces it. Thus, scientists maintaining the Newtonian world view should be unable to communicate with scientists maintaining the relativistic world view. They see and understand the world through radically different lenses. These philosophers were called "radical" because they characterized conceptual change as abrupt and discontinuous, which seemed to imply that scientific change is not a rational process. Significantly, though, what both the positivists and their historicist critics have in common is that the *problem of conceptual change* centers on the nature of the relations between the old and the new linguistic structures.

After much philosophical ink had been spilt in responding to the various conundra which the radical criticisms had raised, such as the problem of incommensurability mentioned above, the problem of conceptual change largely faded from the literature. This occurred not from a sense of the problem having been solved, but rather from a sense of the increasing sterility of the analyses presented. In particular, it seemed that many of the problems might be artifacts of the methodological tools and the implicit presuppositions with which the problem of scientific change, more generally, was being approached. From the perspective of a *cognitive* history and philosophy of science (HPS) that has been developing over the last 15 years, the major stumbling block is in fact how to determine the proper tools of analysis. Cognitive HPS maintains not only that the problem of conceptual change in science lies at the intersection of philosophy, history, and psychology, but that progress towards a solution requires combining the analytical resources and investigative findings of all three in *cognitive-historical* analyses.

First, understanding change requires engaging not simply in endpoints analysis, where the components of the completed conceptual structures are compared, such as in the *mass* example. Fine-structure analyses of scientific practices during the periods of emergence of, and transition between, conceptual structures must be constructed. Second, these examinations of scientific practices need to capture science as conducted in social contexts. These contexts provide material, conceptual, analytical, and cultural resources that facilitate and constrain concept formation and change. Third, scientists bring ordinary human cognitive resources and limitations to bear on their scientific representational, reasoning, and decision-making practices. What we are learning about these in the sciences of cognition need to be incorporated into investigations of scientific practice. The reverse also holds. Current theories of cognitive processes can be evaluated in light of how well they fit the scientific cognition evidenced in the historical cases.

Thus far, no single comprehensive model of conceptual change has emerged through cognitive-historical analysis. Significantly, though, it has recast the problem and set the agenda for contemporary investigations. Cognitive HPS focuses on the practices of scientists in creating conceptual change, not on the conceptual structures per se. Investigations of these practices have led to the view that much conceptual change can be characterized as continuous but noncumulative. For example, it is possible to trace a pattern of descent for the concept of a field from Faraday to Einstein, yet features of Einstein's concept of field are so different from those of any previous concept, such as Faraday's or Maxwell's or Lorentz's, that it cannot be viewed as simply an extension of any of these (see Nersessian, 1984). Research towards an explanatory account that might accommodate this characterization is proceeding in two directions. The first provides a new twist to the traditional problems concerning the nature of the structure of scientific conceptual systems and of the relations among old and new systems. The second addresses a problem traditionally thought to be intractable: the nature of the processes through which new conceptual structures are created.

The first line of research focuses on a central metatheoretical problem: What is the form of the representation of a concept? Underlying both the positivist and the radical historicist accounts is at least tacit acceptance of the *classical* notion that a concept is represented by a set of necessary and sufficient defining conditions. Attempting to fit science concepts and conceptual change into this notion has proved to be notoriously difficult. In science, new concepts are created, such as *spin* in quantum mechanics, and existing ones disappear, such as *phlogiston* from chemistry. However, a significant proportion of concepts in the new system seem to be *conceptual descendants* of existing ones. In the history of science we seem to be able to trace a distinct line of descent and a pattern of progress over time in a conceptual domain using concepts that are not consistent with one another, such as the concept of *inertia* from Galileo to Newton or the concept of *field* from Faraday to Einstein, or even the concept of *mass* from Newton to Einstein. Further, in the case of some, such as *ether*, which appears to have been eliminated, significant aspects have been absorbed by other concepts, in this case *field* and *space-time*. If situations of creation and disappearance were all that one encountered, conceptual change could be characterized fully in terms of the replacement of one structure by another. But, the existence of descendants and of absorption show the need to account for change in individual concepts, as well as entire systems, and to account for it in such a way as to accommodate continuous, noncumulative change at that level. The classical form of representation cannot provide such an account; for, if the defining conditions of a concept were to change, that would simply create a different concept.

Cognitive-historical analysis places the problems that arise with respect to scientific concepts within the context of the problem of human concept representation generally. There is extensive research in cognitive psychology and in psycholinguistics on categorization that provides evidence from ordinary human representation against the classical notion of concepts as well (see Article 25, WORD MEANING, and Article 8, CONCEPTUAL ORGANIZATION). This research was inspired by, and lends empirical support to, an early challenge to the classical notion offered by the philosopher Ludwig Wittgenstein, who argued that it is possible for various instances of a category to be related, even though some of the instances have no features in common (e.g., as in the series AB, BC, CD). He proposed that a better form of concept representation than a definition would be a set of overlapping features, or *family resemblances*.

Although there is consensus that the classical notion of concept representation is inadequate, there is none on which of the several alternative accounts that interpret these data is most satisfactory. Such data and interpretations have been utilized to examine scientific concepts in several different ways. I have adapted a *prototype* notion of a concept, associated with the work of Eleanor Rosch, to develop a *schema* representation of a scientific concept as an overlapping set of features. This analysis enables one to articulate the structure of individual concepts and their interrelations as they have developed over time. Recently Peter Barker and his collaborators (Anderson et al., 1996) have been drawing on the *frame* representation of a concept developed by Lawrence Barsalou (1992) to capture hierarchical and other relations among the features associated with a concept. Their analysis demonstrates how piecemeal transformations in concept frames can end in revolutionary change, making for continuous but noncumulative change. Paul Thagard has drawn on the *WordNet* model of lexical memory developed by George Miller to address the problem of how concepts within a structure are related to one another. This analysis treats concepts as nodes and articulates the structure of conceptual systems in terms of kind and part–whole relations and rules. Further, Thagard (1992) has used this model to argue that *explanatory coherence* of a conceptual system is a primary factor in the choice of one system over another.

The second line of research centers on the practices through which scientific concepts are constructed. Although still in the early stages, this research promises to move beyond description to explanatory accounts of the *mechanisms* or processes of conceptual change. The problem of how new conceptual structures arise was ruled out of philosophical analysis by the logical positivists. They equated scientific method with logic and held that there could be no *logic of discovery*. However, historical analyses across the sciences establish that conceptual innovation and change occur in a problem-solving process. Further, in numerous instances, extensive use is made of heuristics such as analogies, visual representations, and thought-experiments. Are these mere aids to thinking, as construed traditionally, or are they significant mechanisms for generating conceptual changes? The main problem which philosophers have had in even countenancing these as methods is that they are nonalgorithmic in application and even if used *correctly* may lead to the wrong solution or to no solution at all. This very feature, however, makes them more realistic from a cognitive-historical perspective. Scientists often use the same kinds of reasoning to go down fruitless paths as they do in successful outcomes. Viewing these reasoning practices in the light of cognitive research on ordinary reasoning practices provides support for their salience and insight into how they function in scientific reasoning (see Articles 1, 12, 20 and 21: ANALOGY, IMAGERY AND SPATIAL REPRESENTATION, PROBLEM SOLVING, and REASONING).

Cognitive-historical analyses lead to the interpretation that the problem-solving practices exhibited in historical records of concept formation and change are forms of *model-based reasoning*, specifically analogical and imagistic modeling and thought-experimenting and other forms of mental model simulation. Conceptual change often results from a model construction process involving different forms of abstraction (limiting case, idealization, generalization, generic abstraction), constraint satisfaction, adaptation, simulation, and evaluation. To engage in this practice, a scientist needs to know the generative principles and constraints for physical models in one or more domains. New representations are created from existing ones through processes that abstract and integrate source and target constraints into new models. Thus analogy plays a central role in accounting for the continuous, noncumulative nature of conceptual change. But the nature of creative uses of analogy in scientific conceptual changes still needs to be understood better. For example, some cases have involved not simply retrieving ready-to-hand analogies and mapping their salient structures to the new domain, but rather constructing, modifying, and merging imaginary analogs in interaction with constraints of the problem domain under investigation. Further, some reasoning in conceptual change exhibits visual modeling used in conjunction with analogy and dynamical mental simulation. Within cognitive science, analogy, visual representation and reasoning, and mental modeling have been functioning largely as separate areas of investigation. The case of scientific conceptual change shows that a unified account is necessary if we are to construct rich accounts of complex problem solving.

Cognitive development and science learning

Although each of these areas has produced a vast literature on conceptual change, we will discuss both together here, because parallel views in relation to scientific change have arisen in each area. Further, because much cognitive development takes place during the student years, the problems of conceptual change in learning and in development, though often addressed separately, are interrelated. The line of research we will consider in these areas has made considerable use of characterizations of conceptual change developed by philosophers and historians of science. As in the case of scientific change, conceptual change and theory change are thought to be intertwined in development and learning.

Piaget continues to have a profound impact on the current problem situation in these areas. This is especially so with respect to our topic, because the claim that scientific change is relevant to development and learning at all bears his imprint. Piaget's emphasis was on the domain-independent logical structures which he hypothesized were acquired at specific ages. He constructed a *stage theory*, in which cognitive development consists in the unfolding of biologically determined stages, and conceptual change is a process of *assimilation* and *accommodation* through which innate conceptions are restructured in the light of experience. In contrast, the focus of contemporary research has been on the nature of the domain-specific content of children's concepts, such as Susan Carey's (1985) seminal study of the concept of *living thing*. Studies such as those by Carey, Stella Vosniadou and William Brewer (1992), and Alison Gopnik (1996), among others, have led to what has been called the "theory theory account." These psychologists have proposed a theory that the processes of conceptual change in cognitive development take the form of theory formation and change (thus, the *theory theory*). That children converge on specific concepts and theories at roughly the same age is a function of having roughly similar biological theory formation capacities, social supports for learning, and evidential inputs. For many of these researchers, the history of scientific change provides a basis from which to argue that the conceptual changes which children undergo in development are similar in specific characteristics to the kinds of changes in conceptual structure that have taken place in scientific *revolutions*. A similar, related view, now also called the *theory theory*, was proposed earlier in science learning by Michael McClosky (1983) and John Clement (1983) among others. In this domain, the *theory theory* account proposes that students (of all ages) construct intuitive theories of phenomena encountered in their experience. The nature of the ontological commitments and explanatory structure of intuitive theories are thought to be sufficiently different from those of scientific theories to account for the robustness of intuitive concepts in the face of science instruction. Most proponents agree, though, that intuitive theories are rudimentary, and not as systematic and articulated as scientific theories. One implication of the view is that if learning is akin to theory change, difficulty learning abstract scientific concepts may be less a function of a student not having the requisite cognitive resources due to level of development than a function of our not having developed appropriate teaching methods for facilitating change.

Again, these researchers' use of the history of scientific change contrasts with Piaget's. Piaget noted that there are intriguing parallels between conceptualizations of nature produced during the course of cognitive development and those developed over the course of the history of science. He took the parallels to indicate a conceptual form of "ontogeny recapitulates phylogeny" and attempted to fit the entire unfolding of the history of science into the framework of his theory of cognitive development. Contemporary psychologists have continued to find and elaborate intriguing parallels, but their strategy is to use the historical cases to assist in characterizing the kinds of transformations that need to take place in learning and development. The interdisciplinary research area of *cognition and instruction* has made considerable use of the history of scientific change in considering the problem of how to help students learn the conceptual structure of a science. This problem has generated numerous investigations into novice (*naive* or *untutored*) representations of specific domains, including object motion, electricity and magnetism, and human physiology. These investigations comprise a vast and persuasive literature demonstrating that the conceptualizations which students have of many phenomena prior to and often post instruction differ significantly from those of the sciences. Thus, students are thought to have to undergo a major conceptual *restructuring* in order to learn a physical theory.

Despite controversies over the nature of the structures which students may be calling upon and the nature of the *restructuring*, there is widespread agreement that students are not empty vessels into which teachers pour knowledge. This raises the issue of how existing concepts affect learning new material. Take, for example, the case of learning Newtonian mechanics. A nearly universal finding is that students enter (and often exit!) a beginning physics class with a belief that can be characterized as "all motion implies force" (see McDermott, 1984, for a survey). Newtonian mechanics holds that "accelerated motion implies force." Further complicating this learning task, student explanations of motion reveal that their concepts of *motion* and *force* are quite different from the Newtonian concepts. In Newtonian mechanics *motion* is a state in which bodies remain unless acted upon by a force. *Rest* and *motion* have the same ontological status: they are both states. Like rest, motion per se does not need to be explained, only changes of motion. *Force* is a functional quantity that explains changes in motion. Newtonian forces are relations between two or more bodies. Students, however, conceive of *motion* as a process that bodies undergo, and they believe that *all* motion needs an explanation. They conceive of *force* as some kind of power imparted to a body by an agent or another body. This makes *force* ontologically a property or perhaps even an entity, but not a relationship. Thus, learning that "accelerated motion implies force" requires constructing new representations for *motion* and *force* (Nersessian, 1989). That difference in ontological categories is a significant marker of conceptual change figures prominently in Michelene Chi's (1992) recent research on learning. She argues that whole complexes of new ontological categories need to be constructed in order to learn science.

The main support for the psychological hypothesis that conceptual changes in learning and in development are similar to that in scientific change comes from research that describes the initial state of a child's or student's representation of a domain and compares that state with the desired final state. Susan Carey has argued that the *kinds* of change necessary to get from one state to the other resemble those that have taken place in scientific revolutions as characterized by Kuhn (1970). She uses the notion of *incommensurability* between child and adult concepts as evidence of conceptual change in cognitive development. The end-state comparisons, such as in the *motion* and *force* example, do give a sense that the kinds of change necessary for students to learn may be like those in what philosophers and historians of science have characterized as *scientific revolutions*. Significantly, though, even if the *kinds* of change required are strikingly similar in learning, development, and science, this does not mean that the *processes* of change will in any way be alike. It is an open question in need of investigation whether historical conceptual changes can provide models for either learning or cognitive development at the level of processes or *mechanisms* of change.

Implications for cognitive science

Precisely because the advocates of the *theory theory* are not Piagetian with respect to the processes of cognitive development, learning, and conceptual change, they owe us an account of the nature of the processes of conceptual change and of what the activity of *theorizing* comprises, and some are beginning to address these issues. However, cognitive psychologists are still working with accounts of theory and concept formation and change that are influenced by a mixture of earlier empiricist and Kuhnian philosophical accounts, and this presents an obstacle to their undertaking. As we have seen, these accounts provide no insight into the processes of conceptual change. The objectives of those working in development and learning would be better served by collaborating with researchers in cognitive HPS who are addressing the problem of the processes of conceptual change in science. From a cognitive-historical perspective, the problem-solving strategies which scientists have invented and the representational practices they have developed over the course of the history of science are sophisticated, refined outgrowths of ordinary reasoning and representational processes. From childhood through adulthood, ordinary and scientific reasoning and representation processes lie on a continuum, because they originate in modes of learning which evolution has equipped the human child with for survival into adulthood. On this *continuum hypothesis* the cognitive activity of scientists is potentially quite relevant to learning, and vice versa. But again, there are quite difficult questions that need to be addressed in exploring and testing this hypothesis, such as how maturation might complicate learning. Further, in addition to the similarities, there are significant differences that need to be addressed. For example, in cognitive development, change seems just to happen, but in education it requires explicit teaching, and in science it requires explicit and active investigation. Further, in both psychological cases, there are culturally available concepts which the child must acquire in order to mature properly or which we desire them to learn in the educational context, but in the scientific case conceptual change is truly creative. Exploring these and other fundamental questions about the nature and processes of conceptual change in science, cognitive development, and learning in a collaborative undertaking promises to yield richer, possibly unified accounts of this aspect of human cognition.

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