7 Kuhn, Conceptual Change, and Cognitive Science

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7.1 INTRODUCTION

The research project outlined in Thomas Kuhn's *The Structure of Scientific Revolutions* seems intrinsically historical, philosophical, and psychological (Kuhn 1970). However, by and large, Kuhn never utilized research in the cognitive sciences that would have furthered his own paradigm in ways I think he would have found agreeable. Until his very last writings, psychology dropped out of Kuhn's post-*Structure* published articulations of his views just at the time that the cognitive revolution was beginning to provide accounts of representation, problem solving, and learning that I believe are pertinent to his intuitive insights.[1] With hindsight one can construct significant parallels between the views of knowledge, perception, and learning developed in each. In what follows I will discuss in what ways some of Kuhn's insights might be furthered today in light of cognitive science research. Seen through a cognitive lens, Kuhn's little book seems all the more remarkable and insightful. Many of the issues with which he grappled have been the subject of entire areas of research in cognitive science, especially cognitive psychology. In the course of this essay I can only give brief indications of how Kuhn's thinking and research in areas of cognitive science have been running along parallel lines and of how one might, through cognitive-historical analysis, create some intersecting lines.

In his Presidential Address to the Philosophy of Science Association, Kuhn expressed his abiding interest as being in "incommensurability and the nature of the conceptual divide between the developmental stages separated by... 'scientific revolutions' " (Conant and Haugeland 2000, p. 228). In this essay I will focus on three problems of conceptual change: the nature of the representation of a conceptual structure, the processes of learning a conceptual structure, and the processes of creating a conceptual structure. The problems of representation and learning were addressed by Kuhn. Although he recognized the problem of creation, he only briefly

addressed it. The methodological approach I will employ in addressing all three problems is "cognitive-historical" (Nersessian 1992c, 1995b).

The underlying assumption of the cognitive-historical method is a "continuum hypothesis." The cognitive practices of scientists are extensions of the kinds of cognitive practices humans employ in coping with their environment and in problem solving of a more ordinary kind. Employed in analyzing problems relating to conceptual change in science, the "historical" dimension of the method uncovers the representational and reasoning practices scientists use and examines these over extended periods of time and as embedded within local communities and wider cultural contexts. The "cognitive" dimension factors into the analysis considerations of how human cognitive capacities and limitations could produce and constrain the practices of scientists. Thus cognitive-historical analyses, on the one hand, make use of the customary range of historical records and, on the other, draw on extensive scientific investigations into how humans reason, represent, and learn.

However, that ordinary and scientific representational and reasoning practices lie on a continuum does not rule out the possibility of differences. Differences can occur either because they are due to the inherent nature of the activity or because they are an artifact of the fact that much current cognitive science research has been conducted in artificial contexts and on problems of less complexity. My sense is that disparities largely arise because of the latter and that new insights into mundane cognition can be drawn from examining scientific cognition. Thus, the cognitive-historical method is reflexive. Cognitive theories and methods are drawn on insofar as they help interpret the historical cases, while at the same time theories of cognitive processes are evaluated concerning the extent to which they can be applied to scientific practices. Assessments of the fit between the cognitive theories and the scientific practices are fed back into cognitive science to be used in developing richer theories of cognition, which, in turn, will be applied and evaluated in further cognitive-historical analyses. The goal is to bring historical and cognitive interpretations into a state of reflective equilibrium so as to make the circularity inherent in the approach virtuous rather than vicious.

7.2 CONCEPTUAL CHANGE: REPRESENTATION AND PERCEPTION

Most of Kuhn's work after writing *Structure* centered on issues of what he called the scientific "lexicon," specifically, on how the language of a scientific community is acquired and how language change relates to incommensurability. I will begin with Kuhn's theory of concept representation and then move to the issue of the relation between representation and perception. It is in relation to the latter issue that Kuhn himself expressed interest in how research in cognitive science might further his project.

7.2.1 Concept Representation

In the account provided in *Structure* and in Kuhn's later work on the lexicon, concept representation is to be understood in terms of the notion that similarity and dissimilarity to problem exemplars is central to how one acquires the conceptual structure of a paradigm and how one resolves outstanding problems during the course of normal science. What one acquires in learning a conceptual structure are not sets of defining characteristics and specifiable rules for the concepts that participate in the problem exemplars comprised by the paradigm. Rather, one acquires sets of "family resemblances" that include both similarities and differences among instances. In presenting this view, Kuhn explicitly drew from the philosopher Wittgenstein, who in his *Philosophical Investigations* (Wittgenstein 1968) had argued against the "classical" view of concepts, originating with Plato and Aristotle and carried into twentieth-century philosophical analysis by Frege and Russell.

On the classical view, a concept is represented by a definition. A definition is a set of conditions that are singly necessary and jointly sufficient to delineate a concept. Wittgenstein argued that it is impossible to distinguish between "essential" properties of a concept, that is, those that must necessarily be contained in its definition, and "accidental" properties. For example, a flying creature is usually categorized as a 'bird', but 'flies' is a nonessential property, since not all birds fly. What unifies the category of bird is a set of family resemblances among the instances placed in that category. Further, Wittgenstein argued that the instances of some concepts such as 'game' not only cannot be defined by a list of necessary and sufficient conditions but may actually have no one feature in common, and thus each instance shows only a family resemblance to any other.

Kuhn referred to Wittgenstein's analysis in addressing the problem of what is required for there to be consistent application of a paradigm within the community when "the existence of a paradigm need not even imply that any full set of rules exist" (Kuhn 1970, p. 44). He extended Wittgenstein's analysis of concepts such as 'chair' and 'game' to argue that what a scientist knows when participating in a paradigm is not sets of defining criteria and rules, but "various research problems and techniques that... relate by resemblance and by modeling" (ibid., pp. 43–4). In support of his claim, Kuhn invoked the difficulty of formulating the rules that have guided any specific paradigm and the fact that scientists learn paradigms largely by working problem exemplars, not by learning rules and definitions in the abstract. In later work, he focused on the notion that a scientist acquires that part of the paradigm that constitutes its lexicon through a process of learning to discriminate similarities and differences among instances appearing in problem exemplars.

As I and others have noted (Andersen, Chen, and Barker 1996; Chen, Andersen, and Barker 1998; Nersessian 1984b, 1985, 1992b), research on categorization in cognitive psychology begun in the early 1970s by the psychologist Eleanor Rosch and her collaborators provides a cognitive underpinning for many of Kuhn's intuitive insights about concept representation and acquisition. To begin with, the psychological research lends empirical support to the position that in many instances people do not represent concepts by means of sets of necessary and sufficient conditions (see Smith and Medin 1981 for an overview). According to Rosch, this research, too, took its lead from Wittgenstein's critique of the classical view. Rosch began her research with investigations of color categorization and was led to the surprising conclusion that, irrespective of naming practices, the way individuals recognize (i.e., retrieve from memory) colors is not arbitrary, but seemingly is a function of the human perceptual system (Heider 1972). She then extended the research to other perceptual categories, including geometrical shapes, and semantic categories of natural and artificial kinds, such as birds, fruits, clothing, and sports (Rosch and Mervis 1975; Rosch 1987). Other researchers have established the same result for a variety of concepts, including mathematical concepts such as number and plane geometry figures (Armstrong, Gleitman, and Gleitman 1983). Based on the empirical findings, this research program has proposed that, rather than representing concepts by sets of defining criteria, humans represent both natural and artificial concepts by a prototypical example. Category membership is determined by similarity or dissimilarity to the features of the prototype.

Further, concepts show *graded structures*. That is, some instances of a given concept are better examples of the concept than other instances. The classical view cannot be reconciled with the existence of graded structures since, according to it, either a given object fulfills all conditions and therefore is an instance of the concept in question, or it fails to fulfill one or more conditions and therefore is not an instance. On a family resemblance account of concepts, however, some instances may be better examples than others, according to the degree of similarity the object shows to other instances or the degree of similarity the object shows to a prototypical instance. Of course, all instances are members of the category, but some are better exemplars than others. Additionally, categories possess an internal structure: basic level (e.g., bird), subordinate (e.g., Tweety), and superordinate (e.g., animal). The basic level provides the entry point for concept acquisition, naming, and remembering. This is the level at which the members exhibit the highest degree of similarity – especially visual similarity – for human observers. For example, members of the category 'bird' are more similar than those of the category 'animal' (superordinate), and there is no gain – and perhaps some loss – of similarity in the subordinate instances of birds, such as Tweety the canary and Fluffy the parakeet. The hierarchical structure shows that family resemblance concepts form taxonomies. That is, superordinate concepts decompose into more specific, subordinate concepts that may again decompose into yet more specific concepts, and so forth.

Finally, instances of a concept often show not only similarity to other instances of the same concept, but also dissimilarity to instances of other concepts to which the object could otherwise mistakenly have been assigned. To use Kuhn's favorite example, swans may be mistakenly categorized as geese, but instances of the category 'swan' are more similar to instances of the category 'goose' than they are to instances of the category 'dog'. That they can be mistaken for one another also indicates that they form a family resemblance class on the superordinate level. Such a group of concepts that together form a family resemblance class on the superordinate level is called a "contrast set," in this example 'waterfowl'.

The two main accounts of the representation of family resemblance concepts that have been suggested are feature lists and frames. Several varieties of feature-list representations have been proposed. However, these similarity-based representations have been criticized as not providing for well-known effects on categorization, such as context dependence and goals. For example, building nests and laying eggs are typical features of 'bird', but these features have complex relationships to one another, as well as to other features, such as having feathers. To learn what a bird is requires understanding some of these relationships. Thus, simply knowing how instances are similar or dissimilar to the prototype is not sufficient for learning and categorization. So, the empirical evidence strongly suggests that concepts are not represented simply by lists of features, but that the features are organized into more complex structures (Armstrong, et al. 1983; Barsalou 1987;

Medin 1989; Keil 1991). One such structure is a "dynamic frame" (Barsalou 1992), which has been utilized so successfully in the work of Andersen, Barker, and Chen (Andersen et al. 1996; Chen et al. 1998; Andersen and Nersessian 2000) on conceptual change and incommensurability. Since they have an essay in this volume, I will not elaborate on the implications of a dynamic frame-based account of concept representation for understanding conceptual change. It should be noted, though, that their analysis is limited to taxonomic concepts, and the case of science is complicated by the existence of many nontaxonomic concepts, such as 'force' and 'mass'.

Only a limited range of scientific concepts refer to things that can be picked out individually and that form contrast sets (family resemblance on the superordinate level), such as 'duck', 'goose', and 'swan' or 'planet', 'comet', and 'asteroid'. Most scientific concepts such as 'force' and 'electromagnetic field' refer to entities and processes that are learned by apprehending complex problem situations to which a given law applies and in which several concepts are used. For example, what are usually learned are instances of the application of a natural law, such as Newton's second law, $\mathbf{F} = m\mathbf{a}$, in which the concepts 'force', 'mass', and 'acceleration' are involved simultaneously. Kuhn noted this problem on two occasions. In early work, he distinguished between taxonomic scientific concepts, called "basic", and nontaxonomic scientific concepts, called "theoretical" (Kuhn 1970). In later development, he referred to these as "normic" concepts and "nomic" concepts, respectively (Kuhn 1993). In both his earlier and later accounts of this distinction, Kuhn said nothing about how the referents of the individual concepts in such problem situations, here' force', 'mass', and 'acceleration', could be identified (see Andersen and Nersessian 2000 for a fuller discussion).

7.2.2 Concept Representation and Perception

Concept representation and perception are linked in *Structure* through the notion that scientists acquire a paradigm by learning similarity and dissimilarity relations among problem exemplars. Paul Hoyningen-Huene's (1993) analysis of Kuhn's philosophy of science is useful for understanding how this happens. His account provides new insights into Kuhn's views on perception, concept acquisition, and language that are especially useful in thinking about Kuhn's work from a cognitive perspective.

As Hoyningen points out, the account of family resemblance presented in *Structure* went beyond Wittgenstein in claiming that the "sort of world necessary to support the naming procedure" is one in which there must be what Kuhn called "natural families," that is, nonoverlapping or nonmerging families, *and* one that depends for the observer on "the existence, after neural processing, of empty *perceptual space* between the families to be discriminated" (Kuhn 1970, p. 45, fn 2, italics in the original; see also Hoyningen-Huene 1993, p. 85). Kuhn's basic intuition was that the linkage among family resemblance concepts, natural families (or "kinds," as he later refers to them), and human perception creates linkage between conceptual change and perceptual experience. If we connect this intuition to his notion of 'the world' as being constituted by the conceptual structure of a paradigm, we can understand better what Kuhn had in mind in saying that in adopting a new paradigm, one experiences a different world. For him this was not a metaphorical way of speaking but the rudiments of a thoroughly nonrealist position that was never articulated fully.

Change in world-constitutive similarity relations is the hallmark of conceptual change in scientific revolutions. These world-constitutive relations are both learned through and constitutive of perceptual experience. When the representations through which we understand the world change, the world-constitutive similarities and differences that are the focal points of learning and problem solving change. Conceptual change entails perceptual change, and thus incommensurability of experience results as well as incommensurability of language. On Hoyningen's account, Kuhn's shift in focus from the early, largely "perceptual theory" in *Structure* to a focus on language came about for at least three related reasons: first, because of the need to talk about how communities are the agents of scientific activity and how they transmit paradigms and participate in normal scientific research; second, because of his post-*Structure* focus on incommensurability as untranslatability; and third, because of his inability to further articulate the perceptual theory. But, as Hoyningen intimates, the concern to articulate the perceptual theory remained a lifelong concern for Kuhn. The problem of the nature of the linkage between perceptual experience and conceptual change is central to incommensurability. The rudiments of this idea are elaborated in Chapter X of *Structure*, "Revolutions as Changes of World View," which many readers have found perplexing.

Kuhn began the chapter by stating that "The historian of science may be tempted to exclaim that when paradigms change, the world itself changes with them" (p. 111). In this chapter he gave many examples of how postrevolution scientists "lived" and "worked" in a "different world," such as "[a]t the very least, as a result discovering oxygen, Lavoisier saw nature differently. And in the absence of some recourse to that hypothetical fixed nature that he 'saw differently,' the principle of economy would urge us to say that after discovering oxygen Lavoisier worked in a different world" (p. 118). Here Kuhn invoked research in Gestalt psychology to support his insight. The world delimited by a scientific paradigm changes just as the perceived similarity relations change after one learns to conceptualize a Gestalt figure as, for example, a rabbit rather than as what one formally understood as a duck. Soon after the publication of *Structure*, Kuhn backed away from the Gestalt switch metaphor as a category mistake since he had applied to a community a notion that rightly applied only to an individual. He claimed to have relied too much on his own phenomenal experience as a historian attempting to understand Aristotle's worldview. Nevertheless, Kuhn continued to believe that an understanding of how the scientist's experience of the world changes in a revolution needed to be figured into the account of incommensurability. As he stated: "[t]hough the world does not change with the change of paradigm, the scientist afterwards works in a different world. . . . I am convinced that we must make sense of statements that at least resemble these" (p. 121). Kuhn's "linguistic turn" was a shift of focus and not an abandonment of the struggle to construct a viable perceptual theory. In his last published work he characterized the 'lexicon' as the mental "module in which members of a speech community store the community's kind terms" (Kuhn 1993). The lexicon engenders variable beliefs and expectations, depending on an individual's experience and learning. What the community holds in common he called 'lexical structure'. It is difference in lexical structure that creates incommensurability. Different lexical structures embody different kind relations, and these constitute different perceived realities.

On Kuhn's account, then, for conceptual change to take place, the human neural apparatus responsible for processing perceptual stimuli must be capable of being programmed and reprogrammed during the process of exposure to similarity and difference relations and must group perceptions into similarity classes in such a way that they are separated distinctly in perceptual space (Kuhn 1970, pp. 194–7). The Gestalt switch metaphor spoke to the phenomenal experience following a reprogramming through learning the postrevolution conceptual structure. The need to find a way to articulate this intuition accounted for the only interest Kuhn himself showed directly in cognitive science research. His one foray into computational modeling in 1969 was an attempt to model his view of the perceptual reprogramming aspect of conceptual change. In his later years he expressed interest in research on the evolution of the representational capabilities of the brain, cognitive development in children, and computational modeling of learning via neural nets.[2]

In what follows, I will speculate on how Kuhn possibly thought research on cognitive development would help him to articulate the perceptual theory. I say "speculate" since I have not had access to the draft manuscript in which he discusses the cognitive development literature. My account rests on some remarks made in his last writings, the 1990 lecture at UCLA (which he sent to me), "An Historian's Theory of Meaning," the two interviews with him conducted by Hanne Andersen, some discussions I had with him, and my interview with Susan Carey, in which I asked her about details of the material in the cognitive development literature she had discussed extensively with Kuhn and that he noted would play a major role in the analysis in his unfinished book.

The research he mentioned in the materials just noted and, in particular, discussed with Susan Carey concerned the psychological work on criteria for numerical identity and individuation. This research substantiates the existence of an innate representational system through which the brain places constraints on the way objects are individuated and tracked through space and time. Evidence for this system is found in infants as young as two months old in such research as Spelke's (Spelke, Phillips, and Woodward 1995) on object tracking and identification, in which infants show surprise if spatiotemporal continuity is violated for objects. This research provides evidence of tracking for individual objects, not kinds. It is not until around twelve months of age that information about features seems to play a role in object recognition. For example, until that time, when the researcher pulls objects from behind an occluded screen, it does not matter if in one case a boat is revealed and in the other a truck. Babies identify one object, indicating that they are using only spatiotemporal continuity criteria. At about twelve months of age they recognize that there are two objects behind the screen, indicating that they have developed the basis for kind identification. Additionally, research by Pylyshyn (2001) shows there is a midlevel perceptual system operative in adults that also tracks objects in the same way. This system of individuation is perceptually based and operates the same way whether or not the individuals are identifiable members of kinds. The twelve-month system that uses features to keep track of kinds plays a different role in individuation and is both maturation-based and involves learning to determine what kinds the language community discerns. Clearly this builds on the earlier system, and clearly it underlies language learning. In both systems there is a principled distinction between the processes that establish representations of individuals and those that bind features to individuals. The cognitive architecture starts with individuation and only later identifies objects as kinds (see Carey and Fei 2001 for a fuller discussion).

I believe Kuhn saw this work as having the potential to provide a means of furthering his intuition of "empty perceptual space" between the kinds established by a scientific lexicon. In his work on the lexicon, the early notion of "empty perceptual space between families to be discriminated" is related to what he called the "no-overlap principle" for taxonomic categories. According to this principle, no two categories can share a member unless one includes the other totally, such as superordinate categories and their subordinates. Swans and geese are members of the category 'waterfowl', but no swan is a member of the category 'goose'. No two kind terms can share a referent unless there is complete overlap in reference, so 'waterfowl' refers to both swans and geese, but 'swan' cannot refer to a goose. In the world so constituted by this lexicon, there is nothing that is both a swan and a goose. The similarity and difference relations grasped in the learning process constitute both the category and the kind in the world. The no-overlap principle is what makes complete translation impossible between conceptual systems on opposite sides of the revolutionary divide. In posing the problem of incommensurability, Kuhn most often discussed the principle in relation to individuating concepts. However, the psychological research is about constraints on numerical identity and individuation of objects. The function of the cognitive architecture as currently understood is to create *individuals* and track them through time in such a way as for there to be no overlap, not to individuate *concepts* and track them through time. Applying this literature to concepts would be a category mistake. But Kuhn's no-overlap principle has two aspects, one concerning language and the other concerning the world as constituted by that language. The term 'planet' in the Aristotelian lexicon cannot be translated by the term 'planet' in the Copernican–Galilean structure because they refer to different kinds. Kind terms support the categories necessary for describing and generalizing about the world, and different kinds provide for different descriptions and generalizations and thereby, experientially, different worlds.

Kuhn stated that his intention in the forthcoming book was to "suggest that this characteristic [no-overlap] can be traced to, and on from, the evolution of the neural mechanisms for reidentifying what Aristotle called 'substances': things that, between their origin and demise, trace a lifeline through space over time" (Conant and Haugeland 2000, p. 229). Here he referred to philosophical work on sortals (Wiggins 1980), which like the psychological literature on the early individuation system pertains only to substances, not kinds. How Kuhn might have seen the extension to kinds working out is as follows. There is an innate mechanism that embodies a no-overlap principle for tracking and individuation. This is a perceptually based system that works regardless of whether the individuals are kinds or not. On top of this builds the mature system, which plays a different role in individuation by means of kinds. It uses properties that enable discrimination (similarity and difference relations) to keep track of kinds and also embodies a no-overlap principle for kinds. Its development is a function of maturation and learning that is tied to language. But, as Kuhn noted, for his purposes a broader notion of 'kind' than is customary is needed, one that will "populate the world as well as divide up a preexisting population" (ibid., p. 229). In this case, the mature cognitive system would need to be capable of being reprogrammed to identify the new kinds created in a scientific revolution.

7.3 CONCEPTUAL CHANGE: LEARNING IN SCIENCE EDUCATION

As discussed in Section 7.2, Kuhn's theory of concepts derives from his insight that learning from problem exemplars provides entrée into the linguistic community of a science. The original insight involved more than learning concepts since problem exemplars also provide knowledge of other aspects of scientific practice such as knowledge of methods and analytical techniques and of how mathematical relations map to physical situations. Kuhn saw science education as a process of indoctrination in which textbook distillations and reformulations of current knowledge are the chief pedagogical tools. Repeatedly working problem sets and assimilating the similarities and differences among problem exemplars enables the learner to acquire the paradigm and thus the means for solving outstanding problems during the course of normal science. Kuhn also believed this pedagogical approach to be highly successful and one that should be continued since "[n]othing could be better calculated to produce 'mental sets' or *Einstellungen*" (Kuhn 1977, p. 229).

However, as Kuhn noted, there is something paradoxical about the apparent success of this pedagogical method. Consider the following problems. First, since textbook presentations do not represent the kinds of problems experts will need to solve and the range of methods for solution, how is the textbook method so successful at producing practitioners of "normal science"? Textbooks present problems analogous to paradigmatic examples of solved problems, and laboratory exercises largely present "canned" experiments related to these. In both cases, exemplars are not presented in the form practitioners will encounter or with many of the techniques needed to tackle the authentic problems. Yet the method seems to produce

competent puzzle solvers for the existing tradition. Second, "followed by a term in an apprenticeship relation, this technique of exclusive exposure to a rigid tradition has been immensely productive of the most consequential sorts of innovation" (ibid., pp. 229–30) Although Kuhn is right in pointing out that there is an "essential tension" between innovation and tradition, what he failed to appreciate fully is that it is mitigated by the flexibility in the apprenticeship learning component of training practitioners. Cognitive science research indicates that there are no paradoxes with respect to the traditional pedagogical method. The textbook-type science education has *not* been successful in producing practitioners. Very few students learn the subject sufficiently well even to provide explanations and predictions of simple physics phenomena, never mind to go on to graduate school and become practitioners. Much of the credit for the success in creating practitioners goes to the apprenticeship – usually experienced first in graduate school – during which practices are learned in authentic situations. In apprenticeships, students learn the tacit as well as the explicit practices of the discipline. Within cognitive science such situated learning experiences have been called "cognitive apprenticeships" (Brown, Collins, and Duguid 1989; Collins, Brown, and Duguid 1989). In this form of training, science students learn, among other things, how to adapt problem exemplars to current research problems by observing how practitioners tackle these and participating in the research. In this process they are exposed directly to the formal and informal methodological practices, conceptual understandings, and interpretive structures that constitute the practice of the science.

7.3.1 Cognitive Research on Physics Education

If we focus just on the dimension of conceptual change, cognitive science research on learning in physics education shows that traditional undergraduate instructional techniques and textbooks are spectacularly *un*successful at facilitating the process of students learning the conceptual structure of physics. A substantial body of literature has established quite conclusively that even after training in physics, large numbers of students, including those who have learned to perform the requisite calculations, have not learned the scientific conceptual structure of the domain (Driver and Easley 1978; Viennot 1979; Champagne, Klopfer, and Gunstone 1982; Clement 1982; McCloskey 1983; McDermott 1984; Halloun and Hestenes 1985). In numerous studies of varying design, the qualitative explanations students give for various phenomena after instruction in science are at odds with those given by physics. The source of the difficulty is widely held to be the fact that students come to their physics classes with preconceptions about the nature and processes of such phenomena as motion that, though not fully developed and integrated, interfere with learning science. Thus, students are thought to have to undergo major conceptual change in the learning process.

Much of the research on learning in physics has focused on Newtonian mechanics since it is with mechanics that most students first encounter an abstract, formal scientific theory. Based on numerous studies of "restructuring," "conceptual change," and "naive physics" (Viennot 1979; Clement 1982, 1983; McCloskey 1983; McDermott 1984; Nersessian 1989; Nersessian and Resnick 1989; Chi 1992), it has been established that intuitive physical explanations, such as those of motion, differ from scientific explanations along several dimensions. These explanations employ concepts of a kind different from those used in scientific explanations, most notably with respect to ontological status and level of abstraction. For example, students conceive of objects, such as stones, rather than mathematical point masses; they think of force as a property of objects rather than a relation between objects; and they view motion as a process rather than as a state.

The intuitive conceptualizations of many of the phenomena present obstacles to learning. To see this, an example that I have discussed in some detail in previous work (Nersessian 1989; Nersessian and Resnick 1989) will be useful. From what we know thus far, in learning Newtonian mechanics students must change from believing that "motion implies force" to believing that "accelerated motion implies force." However, examining student protocols before and after-instruction reveals that their concepts of 'motion' and 'force' are not the same as the Newtonian concepts. In Newtonian mechanics, motion is a state in which bodies remain unless acted on by a force. Thus, 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 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. On the whole, the concepts students intuitively employ to understand how objects move resemble more the Aristotelian/medieval concepts than the Newtonian understanding needed to acquire the science, which is most likely due to their experiences in a world of friction. And

studies show that the intuitive conceptual structure is largely untouched by traditional science instruction.

From the cognitive research, it appears that learning a scientific conceptual structure requires the student to construct fundamentally new concepts and to build them into a new framework. By and large, Kuhn is correct that in the traditional textbook concepts are introduced by means of equations said to "define" them (such as " 'force' is defined as $\mathbf{F} = m\mathbf{a}$"), and these are accompanied by problem exemplars the concepts are instantiated by and by "canned" laboratory exercises that exemplify them. The expectation is that students will learn to apply the concepts by extracting them from the problem exemplars. The result of this pedagogical approach is that the majority of students leave their physics classes with their "intuitive" or "naive" conceptualizations of physical phenomena largely intact and without the ability to provide scientific explanations of these phenomena. One possible reason why it is difficult to learn the conceptual structure by this method is that, as discussed in Section 7.2, unlike concepts of ordinary language such as 'swan', most science concepts appear together in complex problem situations. Thus something more is needed for conceptual change than learning similarity and difference relations among problem exemplars.

Research on learning in science education and in cognitive development are areas of cognitive science where Kuhn's early views on scientific revolutions and incommensurability have had significant influence. Many researchers have proposed an analogy between the kinds of changes in conceptual structure required in learning and those that have taken place in scientific revolutions. The main support for hypotheses drawn from the analogy comes from research that describes the initial states of learners and compares these with the desired final states. These end-state comparisons, such as provided in the 'motion' and 'force' example, do give a sense that the kinds of conceptual changes students need to undergo to learn may be akin to those that take place in what philosophers and historians of science have characterized as "scientific revolutions." However, even if the *kinds* of changes are strikingly similar, this does not mean that the *processes* of change need in any way be alike. The focus of this research has been on providing analyses of differences between the content, structure, and characteristics of the knowledge on which students and scientists draw, with scant attention being directed to the methods for constructing conceptual structures. The problem of how change is created or the nature of what psychologists call the "mechanisms" of change is just beginning to be addressed in a rigorous way.

Likening the changes and processes of learning and development to those of scientific revolutions does not, of course, solve the problem; it just displaces it. Those who study scientific change have not solved the problem either. In earlier work, I proposed that a promising way of addressing the problem is through extending the analogy to the mechanisms of conceptual change (Nersessian 1992a, 1995c). This move is warranted on the basis that the cognitive tasks in the learning process and in the initial constructive process are similar in salient ways. In both cases, what is needed is to construct new concepts, form new conceptual structures, and integrate the new representation for coherent, systematic use. This is so despite the fact that, in the case of learning, teachers possess the extant knowledge students need to learn, and in the case of first constructing the concepts no one had the answer. The proposal that the cognitive processing required to build a conceptual structure is similar in the two cases is in line with research investigating the hypothesis that cognitive development and learning involve processes of theory change and conceptual change that are similar to those of scientific theorizing and conceptual change (Carey 1985, 1991; Chi 1992; Gopnik and Meltzoff 1997). The point is that the high degree of similarity in the nature of the kinds of changes indicates a relationship in the cognitive tasks. It follows from the proposal that pedagogy and practice would need to be brought more into line. The cognitive procedures employed in the actual construction of concepts should be effective in pedagogical situations. There is precedent for this approach in scientific practice itself. Often when a scientist who has constructed a new conceptualization attempts to communicate it to his peers, the same constructive procedures are employed, effectively leading colleagues through the process of learning the new framework.

Although he did not apply it to his theory of science learning, Kuhn clearly saw what is wrong with the textbook approach. The "concept of science drawn from them is no more likely to fit the enterprise that produced them than an image of a national culture drawn from a tourist brochure or a language text" (Kuhn 1970, p. 1). So, how to determine what the constructive practices are?

7.3.2 A Role for History? Mining the History of Science

The proposal made in the previous section differs significantly from "recapitulation" theories in science education with which it might be compared. Although there are interesting parallels between historical prescientific conceptions in some domains and untutored conceptions, "recapitulating" the historical process is neither possible nor feasible nor desirable. Rather, the suggestion is that the cognitive practices of scientists provide a model for

cognitive aspects of the learning activity itself, and with respect to the problem of conceptual change, the history of science is a source for discerning these. For the purposes of developing new pedagogical approaches, the history of science can be viewed as a repository of strategic knowledge of how to go about constructing, changing, and communicating scientific representations. The recommendation, then, is that researchers "mine" the historical data for this knowledge, develop analyses of how the practices are generative, and use what they learn in developing instructional procedures.

Possibly the most widely quoted sentence drawn from philosophy and history of science is that with which Kuhn opened *Structure*: "History, if viewed as a repository for more than anecdote or chronology, could produce a decisive transformation in the image of science by which we are now possessed" (p. 1). In that work Kuhn saw himself as shifting the focus of philosophical analysis from a static view of science to the dynamical perspective opened by examining the history of scientific practices. However, his later shift to language analysis ultimately led him to abandon history as a source for building a theory of scientific change. As he stated in the Rothschild Lecture at Harvard in 1992:

> Given what I shall call the historical perspective, one may reach many of the central conclusions we drew with scarcely a glance at the historical record itself. That historical perspective was, of course, initially foreign to all of us. The questions which led us to examine the historical records were products of a philosophical tradition that took science as a static body of knowledge and asked what rational warrant there was for taking one or another of its component beliefs to be true. Only gradually, as a by-product of our study of historical "facts," did we learn to replace that static image with a dynamical one, an image that made science an ever-developing enterprise or practice. And it is taking longer still to realize that, with that perspective achieved, many of the most central conclusions we drew from the historical record can be derived instead from first principles. Approaching them in that way reduces their apparent contingency, making them harder to dismiss as a product of muckraking investigations by those hostile to science. (Kuhn 1992, p. 10; see also Kuhn 1990, p. 6)

I agree with the dynamical image of science and share Kuhn's concerns about contingency, but the question remains: where do the "first principles" arise? In shifting from examining practices, Kuhn sought these through thinking about languages and how they are learned. In this he reverted to the strategy employed by the static approach of placing the analytical focus on the linguistic dimension of scientific conceptual structures and transferring to science what might be said of languages generally. Clearly scientific conceptual structures can be represented linguistically. But this does not mean that we can learn about the nature of conceptual change in science simply – or even mainly – by investigating the nature of languages and language learning. One important difference between an ordinary language and the language of a science is that the former does not change as drastically as the latter can within a short span of time. Kuhn is right that the history of science has shown us that science is dynamic, continually undergoing processes of construction and refinement. But considering how a language is acquired and transmitted within a community does not address the dynamics of how languages are constructed and change, which is what is required in attacking significant aspects of the problems of conceptual change and incommensurability.

Clearly also, a way needs to be devised to handle the problem of the "apparent contingency" and particulars of case studies within a more general account of the nature of concept formation and change in science. By placing the historical practices within the broader framework of human cognitive activities, cognitive-historical analysis goes beyond the specific case study to more general conclusions about the nature and function of the scientific practices. Such placement aids in establishing that the fragments of scientific research and discovery are representative of scientific practices more generally. As Hutchins has said of studies of situated cognitive practices generally:

> There are powerful regularities to be described at a level of analysis that transcends the details of the specific domain. It is not possible to discover these regularities without understanding the details of the domain, but the regularities are not about the domain specific details, they are about the nature of cognition in human activity. (Woods 1995, p. 15)

I believe Kuhn's earlier insight that a theory of conceptual change would have to be grounded in an examination of the history of scientific practices has not yet been fully exploited. As noted earlier, Kuhn did not address the problem of creating conceptual structures, but from a cognitive-historical perspective the resolution of the problem has implications for the problems of representation and learning. The problem of creation requires grounding in history. Cognitive-historical research shows the constructive practices of scientists in creating new conceptual structures to involve, centrally, model-based reasoning. In the following sections I will provide brief indications of how they function.

7.4 CONCEPTUAL CHANGE: THE ROLE OF MODEL-BASED REASONING

On the Kuhnian model, conceptual change arises from a pattern that consists of an accumulation of anomalies, then a crisis, and then a new conceptual structure that forms as part of a new paradigm. However, the processes through which the new conceptual structure arises are left mysterious. The radical discontinuity view many interpreters have read into Kuhn's work is decidedly unhistorical, and Kuhn, having carried out many historical analyses, could not subscribe to it. Instead, he maintained from the outset that "[n]ew theories . . . in the mature sciences are not born *de novo*. On the contrary, they emerge from old theories. . . ." (Kuhn 1977, p. 229); thus "since the new paradigms are born from old ones, they ordinarily incorporate much of the vocabulary and apparatus, both conceptual and manipulative" of the old paradigms (Kuhn 1970, p. 149). A central contention of the cognitive-historical approach is that the answer to the question of how they are "born from new ones" lies in examining the representational and reasoning practices employed by scientists in constructing new conceptual structures. Through understanding these, an account can be developed of (1) the nature of the commensurability relations that Kuhn intimated to exist between successive representations of a domain and (2) whether and, if so, what kinds of domain-independent constructive practices exist in science. In determining the practices, historical analysis continues to play a central role. But there is also a need to move beyond a historical analysis that describes those practices to an explanatory account that utilizes them in addressing the generative problem of how the reasoning creates new conceptual structures from existing ones.

Although, again, it is not possible to go into the details in depth within the confines of this essay, my account of how model-based reasoning practices are generative of conceptual change derives from extensive historical and cognitive research. The scientific practices are determined by historical research and investigations of contemporary practices by cognitive scientists. These provide the focal points for examining cognitive science research in search of findings that help to explain the cognitive underpinnings of the scientific practices, to formulate hypotheses about why these practices are effective, and to discern ways in which the cognitive research might be challenged by the findings from examining scientific cognition. The cognitive science research pertinent to model-based reasoning is drawn primarily from the literatures on analogy, mental modeling, mental simulation, mental imagery, imagistic and diagrammatic reasoning, expert/novice problem solving, and conceptual change.

The nature of the specific conceptual, analytical, and material resources and constraints provided by the sociocultural environments within and external to the scientific communities in which conceptual changes have taken place have been examined for many episodes and sciences. What stands out from this research is that, in numerous instances of "revolutionary" conceptual change across the sciences, the practices of analogy, visual representation, and thought experimenting are employed. My own historical investigations center on practices employed in physics (Nersessian 1984a, 1984b, 1985, 1988, 1992b, 1992c, 1995b, in press-a, in press-b), but those of other sciences by philosophers, historians, and cognitive scientists establish that these practices are employed across the sciences (see, e.g. Rudwick 1976; Darden 1980, 1991; Holmes 1981, 1985; Latour 1986; Latour and Woolgar 1986; Tweney 1987, 1992; Giere 1988, 1992, 1994; Griesemer and Wimsatt 1989; Gooding 1990; Lynch and Woolgar 1990; Griesemer 1991a, 1991b; Thagard 1991; Shelley 1996; Gentner and Markman 1997; Trumpler 1997). In these practices reasoning is model-based, that is, inferences are made from and through constructing and manipulating models.[3] What the historical and contemporary cases show is that constructing new representations in science often starts with modeling, and this is followed by the quantitative formulations found in the laws and axioms of theories. Model-based reasoning practices are used in communicating novel results and instructing peers within the community in the new representations. Although these practices are ubiquitous and significant, they are, of course, not exhaustive of the practices that generate new representational structures.

7.4.1 Mental Modeling

Within contemporary cognitive science, the hypothesis of reasoning via "mental modeling" serves as a framework for a vast body of research that examines understanding and reasoning in various domains including reasoning about causality in physical systems (see, e.g., DeKleer and Brown 1983), the role of representations of domain knowledge in reasoning (see, e.g., Gentner and Stevens 1983), logical reasoning (see, e.g., Johnson-Laird 1983), discourse and narrative comprehension (see, e.g., Johnson-Laird 1983; Perrig and Kintsch 1985), and induction (see, e.g., Holland, Holyoak, Nisbett, and Thagard 1986). Additionally, there is considerable experimental protocol evidence collected by cognitive researchers that supports claims of mental modeling as significant in the problem-solving practices of contemporary scientists (see, e.g., Chi, Feltovich, and Glaser 1981; Clement 1989; Dunbar 1995, 1999).

Mental modeling, a semantic process thought to utilize perceptual mechanisms in inference, is hypothesized by many cognitive scientists to be a fundamental form of human reasoning. They speculate that the ability evolved as an efficient means of navigating the environment and solving problems in matters of significance to existence in the world. Thus the ability is hypothesized to exist in many creatures, with humans having the ability to create models from both perception and language and having extended its use to esoteric situations such as scientific reasoning. The interpretation of the evidence amassed in the investigations noted previously and numerous others is consistent with the contention that mental modeling is applied across a spectrum of problem-solving situations and in numerous domains, ranging from solving the problem of how to get a chair through a doorway to problems related to narrative and discourse comprehension to problems traditionally classified as falling within the province of deductive and inductive logic. The modeling process is hypothesized to be generative in reasoning because specific inferences can be traced directly to a model.

In the process of mental modeling, a structural or functional analog of a real-world or imaginary situation, event, or process is constructed. The mental model embodies a representation of the salient spatial and temporal relations among and the causal structures connecting the events and entities depicted and other information that is relevant to the problem-solving task. A mental model is not a mental image, although in some instances an image might be employed. It is an analog in that it preserves constraints inherent in what is represented. The representation is intended to be isomorphic to dimensions of the real-world system salient to the reasoning process. Thus, for example, in reasoning about a spring, the mental model need not capture the three-dimensionality of a spring if that is not taken to be relevant to the specific problem-solving task. The nature of the representation is such as to enable simulative behavior in which the models behave in accord with constraints that need not be stated explicitly. For example, for those tasks that are dynamic in nature, if the model captures the causal coherence of a system, it should, in principle, be possible to simulate the behaviors of the system. Thus, the inferential process is one of direct manipulation of the model. Cognitive science claims about the specific nature of the model-manipulation process are linked to the nature of the format of the representation. I will not go through numerous format issues here. It is sufficient to say that mental models are schematic in that they contain selective representations of aspects of the objects, situations, and processes and are thus flexible in reasoning and comprehension tasks.

Only a "minimalist" mental modeling hypothesis is needed in support of the contention that it provides a cognitive basis for taking seriously the modeling practices of scientists as generative in creating conceptual structures: in certain problem-solving tasks, humans reason by constructing an internal model of the situations, events, and processes that in dynamic cases can be manipulated through simulation. Information in various formats, including linguistic, formulaic, visual, auditory, and kinesthetic, can be used in its construction. In mundane cases, the reasoning performed is usually successful. One figures out how to get the chair through the door by means of mental simulation because the models and manipulative processes embody largely correct assumptions about everyday real-world events. In the case of science, where the situations are more removed from human sensory experience and the assumptions are more imbued with theory, there is less assurance that a reasoning process, even if carried out correctly, will yield success. In the evaluation process, a major criterion of success remains the goodness of the fit to the phenomena. The hypothesis is minimalist because it bypasses several issues about the nature of the format of the model and the processes of simulation that are in contention in cognitive science. The cognitive notion of reasoning via mental modeling fits well with the contemporary philosophical claims that scientists apply theories by reasoning with models (Cartwright 1983; Giere 1988; Magnani, Nersessian, and Thagard 1999; Morgan and Morrison 1999). The basic idea is that no matter how scientific theories may *in principle* be represented, models are the mental representations with which a scientist carries out much reasoning and by means of which she thinks and understands through the lens of a conceptual structure. The claim advanced in my research is that modeling, too, plays a central role in how new representations are constructed by scientists.

7.4.2 Model-Based Reasoning

Although in a modeling episode analogy, imagistic reasoning, and thought experimenting are often employed together, I will first discuss how they function separately and then consider what features they share. As with the preceding discussions, only a sketch of an analysis will be presented.

As employed in model-based reasoning, analogies serve as sources of constraints for constructing models. To engage in analogical modeling, one calls on knowledge of the generative principles and constraints for physical models in a source domain. These constraints and principles may be represented mentally and externally in different informational formats

and knowledge structures that act as tacit assumptions employed in constructing and transforming models during problem solving. The cognitive literature agrees with the position that analogies employed in conceptual change are not merely guides to reasoning but are generative in the reasoning processes in which they are employed. For example, in investigations of analogies used as mental models of a domain, it has been demonstrated that inferences made in problem solving depend significantly on the specific analogy in terms of which the domain has been represented. One example is a study in which subjects constructed a mental model of electricity in terms of an analogy with either flowing water or teeming objects. Specific inferences, sometimes erroneous, in problem solutions could be traced directly to the specific analogy employed in representing the domain (Gentner and Gentner 1983). Here the inferential work in generating the problem solution clearly was done by using the analogical models.

A reasoning process I have called "generic abstraction" is key in analogical modeling in conceptual change. Conceptual innovation often requires recognition of potential similarities across, and integration of information from, disparate domains. In viewing a model generically, one takes it as representing features common to a class of phenomena. This way of viewing the model can, of course, take place only in the mind. In reasoning, for example, about a triangle, one often draws or imagines a concrete representation. However, to consider what it has in common with all triangles, one needs to imagine it as lacking specificity in the angles and the sides. That is, the reasoning context demands that the interpretation of the concrete polygon be as generic. It was through generic abstraction, for example, that Newton could reason about the commonalities among the motions of planets and of projectiles, which enabled him to formulate a unified mathematical representation of their motions. The analogical model, understood generically, represents what is common among the members of specific classes of physical systems viewed with respect to a problem context. Newton's inverse square law of gravitation abstracts what a projectile and a planet have in common in the context of determining motion. After Newton, the inverse square law model served as a generic model of action-at-a-distance forces for those who tried to bring all forces into the scope of Newtonian mechanics.

A variety of perceptual resources can be employed in modeling. Here I focus on the visual modality since it figures prominently in cases of conceptual change across the sciences. There is a vast cognitive science literature on mental imagery that provides evidence that humans can perform simulative imaginative combinations and transformations that mimic perceptual spatial transformation (Kosslyn 1980; Shepard and Cooper 1982). These simulations are hypothesized to take place using internalized constraints assimilated during perception and motor activity (Kosslyn 1994). Other research indicates that people use various kinds of knowledge of physical situations in imaginary simulations. For example, when objects are imagined as separated by a wall, the spatial transformations exhibit latency times consistent with having simulated moving around the wall rather than through it. There are significant differences between spatial transformations and transformations requiring causal and other knowledge contained in scientific theories. Although the research on imagery in problem solving is scant, recently cognitive scientists have undertaken several investigations examining the role of causal knowledge in mental simulation involving imagery; for example, experiments with problems employing gear rotation provide evidence of knowledge of causal constraints being utilized in imaginative reasoning (Hegarty 1992; Hegarty and Sims 1994; Hegarty and Steinhoff 1994; Schwartz and Black 1996).

The hypothesis that internal representations can be imagistic does not mean that they need to be picturelike. They can be highly schematic in nature. The claim is only that they are modal representations that employ perceptual and possibly motor mechanisms in processing. Thus the fact that some scientists such as Bohr claim not to experience mental pictures in reasoning is not pertinent to the issue of whether this kind of perceptual modeling is playing a role in the reasoning. External visual representations (including those made by gesturing and sketching) employed during a reasoning process are a significant dimension of cognitive activity in science and should be analyzed as part of the cognitive system. These representations can be interpreted as providing support for the processes of constructing and reasoning with a mental model. In model-based reasoning processes, they function as much more than the external memory aids they are customarily considered to be in cognitive science. They aid significantly in organizing cognitive activity during reasoning, such as fixing attention on the salient aspects of a model, enabling retrieval and storage of salient information, and exhibiting salient constraints, such as structural and causal constraints, in appropriate colocation. Further, they facilitate construction of shared mental models within a community and transportation of scientific models out of the local milieu of their construction.

Imagistic representations in physics participate in modeling phenomena in several ways, including providing abstracted and idealized representations of aspects of phenomena and embodying aspects of theoretical models. For example, early in Faraday's construction of an electromagnetic field concept, the visual model he constructed of the lines of force provided an idealized representation of the patterns of iron filings surrounding a magnet. However, cognitive-historical research substantiates the interpretation that later in his development of the field concept, the imagistic model functioned as the embodiment of a dynamical theoretical model of the transmission and interconversion of forces generally through stresses and strains in, and various motions of, the lines (Gooding 1981; Nersessian 1984b, 1985; Tweney 1985, 1992). But, as I have argued (Nersessian 1984b, 1992, in press-a, in press-b), the visual representation Maxwell presented of the idle wheel-vortex model of the electromagnetic aether was intended as an embodiment of an imaginary system. Its function was to capture a generic dynamical relational structure, not to provide a representation of the theoretical model of electromagnetic field actions in the aether.

As a form of model-based reasoning, thought experimenting can be construed as a specific form of simulative reasoning in mental modeling. In simulative reasoning, inferences are drawn by employing knowledge embedded in the constraints of a mental model to produce new states. Constructing a thought-experimental model requires understanding the salient constraints governing the kinds of entities or processes in the model and the possible causal, structural, and functional relations among them. Conducting a simulation can employ either tacit or explicit understanding of the constraints governing how those kinds of things behave and interact and how the relations can change. A simulation creates new states of a system being modeled, which in turn creates or makes evident new constraints. Changing the conditions of a model enables inferences about differences in the way that a system can behave. Various kinds of knowledge of physical situations are employed in imaginary simulations. Because the simulation complies with the same constraints of the physical system it represents, performing a simulation with a mental model enables inferences about real-world phenomena to be drawn. Note that understanding of the mathematical constraints governing a situation is one kind of knowledge that can be used in simulative reasoning by scientists.

In the case of scientific thought experiments implicated in conceptual change, the main historical traces are in the form of narrative reports, constructed after the problem has been solved. These reports have often provided a significant means of effecting conceptual change within a scientific community. Accounting for the generative role of this form of model-based reasoning begins with examining how these thought-experimental narratives support modeling processes and then making the hypothesis that the original experiment involves a similar form of model-based reasoning.

From a mental modeling perspective, the function of the narrative form of presentation of a thought experiment would be to guide the reader in constructing a mental model of the situation described by it and to make inferences through simulating the events and processes depicted in it. A thought-experimental model can be construed as a form of "discourse" model studied by cognitive scientists, for which they argue that the operations and inferences are performed not on propositions but on the constructed model (see, e.g., Johnson-Laird 1983, 1989; Perrig and Kintsch 1985; Morrow, Bower, and Greenspan 1989). Simulation is assisted in that the narrative delimits the specific transitions that govern what takes place. The thought-experimental simulation links the conceptual and experiential dimensions of human cognitive processing (see also Gooding 1992). Thus, the constructed situation inherits empirical force by being abstracted both from experiences and activities in the world and from knowledge, conceptualizations, and assumptions of it. In this way, the data that derive from thought experimenting have empirical consequences and at the same time pinpoint the locus of the needed conceptual reform.

Unlike a fictional narrative, however, the context of the scientific thought experiment makes it clear to the reader that the inferences made pertain to potential real-world situations. The narrative has already made significant abstractions, which aid in focusing attention on the salient dimensions of the model and in recognizing the situation as prototypical (generic). Thus, the experimental consequences are seen to go beyond the specific situation of the thought experiment. The thought-experimental narrative is presented in a polished form that works, which should make it an effective means of generating comparable mental models among the members of a community of scientists.

The processes of constructing the thought-experimental model in the original experiment would be the same as those involved in constructing any mental model in a reasoning process. In conducting the original thought experiment, a scientist would make use of inferencing mechanisms, existing representations, and scientific and general world knowledge to make constrained transformations from one possible physical state to the next. Thus, competence in constructing models and simulations should be a function of expertise. As with real-world experiments, some experimental revision and tweaking undoubtedly goes on in conducting the original and in the narrative construction, although accounts of this process are rarely presented by scientists.

Finally, in mundane cases, the reasoning performed via simulative mental modeling is usually successful because the models and manipulative

processes embody largely correct constraints governing everyday real-world events. Think, for example, of how people often reason about how to get an awkward piece of furniture through a door. The problem is usually solved by mentally simulating turning over a geometrical structure approximating the configuration of the piece of furniture through various rotations. The task employs often implicit knowledge of constraints of such rotations and is often easier when the physical chair is in front of the reasoner, acting to support the structure in imagination. As was said earlier, in the case of science there is less assurance that a simulative reasoning process, even if carried out correctly, will lead to a successful outcome – or any outcome at all.

Having considered the model-based reasoning practices separately, we can now extract several key common ingredients. The problem-solving processes in which they are employed involve constructing models that are of the *same kind* with respect to salient dimensions of target phenomena. The models are intended as interpretations of target physical systems, processes, phenomena, or situations. The modeling practices make use of both highly specific domain knowledge and knowledge of abstract general principles. Further, they employ knowledge of how to make appropriate abstractions. Initial models are retrieved or constructed on the basis of potentially satisfying salient constraints of the target domain. Where the initial model does not produce a problem solution, modifications or new models are created to satisfy constraints drawn from an enhanced understanding of the target domain and from one or more source domains (the same as the target domain or different). These constraints can be supplied by means of linguistic, formulaic, and imagistic (all perceptual modalities) informational formats, including equations, texts, diagrams, pictures, maps, and physical models. In the modeling process, various forms of abstraction, such as limiting case, idealization, generalization, and generic modeling, are utilized, with generic modeling playing a highly significant role in the generation, abstraction, and integration of constraints. Evaluation and adaptation take place in light of structural, causal, and/or functional constraint satisfaction and enhanced understanding of the target problem that has been obtained through the modeling process. Simulation can be used to produce new states and to enable evaluation of behaviors, constraint satisfaction, and other factors. Clearly, scientists create erroneous models, so revision and evaluation are crucial components of model-based reasoning. In the evaluation process, a major criterion is goodness of fit to the constraints of the target phenomena, but success can also include such factors as enabling the generation of a viable mathematical representation that can push the science along while other details of representing the phenomena are still to be worked out, as

Newton did with the concept of gravitation and Maxwell with the concept of the electromagnetic field.

To explain why modeling practices figure centrally in conceptual change in science requires a fundamental revision of the understandings of concepts, conceptual structures, conceptual change, and reasoning customarily employed explicitly in philosophy and at least tacitly in the science studies fields more generally. The basic ingredients of that revision are to view a concept as providing a set of constraints for generating members of a class of models and a conceptual structure as an agglomeration of constraints. Concept formation and change is a process of generating new and changing existing constraints. Model-based reasoning promotes conceptual change because it is an effective means of abstracting, generating, integrating, and changing constraints. The domain-independent reasoning practices of analogy, visual modeling, and thought experimenting are prevalent in periods of radical conceptual change because they are highly effective means of making evident and abstracting constraints of existing representational systems and, in light of constraints provided by the target problem, effective means of integrating constraints from multiple representations such that truly novel representational structures result.

Finally, with respect to the role of model-based reasoning in facilitating conceptual change in learning, cognitive research shows that novice students do not have knowledge of the scientific constraints of physical domains and do not know how to view problem exemplars generically (how to abstract constraints). However, they do possess the basic cognitive capacities employed in model-based reasoning: to make analogies, to create mental simulations, and to perform idealization and generic abstraction. Potential developmental factors relating to the ability to employ these kinds of procedural knowledge explicitly are currently not well understood and are in need of investigation. It is clear that students do need explicit instruction in how to employ this procedural knowledge in scientific problem solving. Cognitive-historical research is playing a role in the development of successful model-based learning environments in K-12 physics education (Smith, Snir, and Grosslight 1992; Carey and Smith 1993; Wiser 1995; Jiminez Gomez and Fernendaz Duran 1998).

7.5 CONCLUSION

Problems relating to conceptual change were the focus of Thomas Kuhn's intellectual life. These are difficult but – I believe – not intractable problems.

What makes them especially difficult is that they lie at the interface of history, philosophy, and psychology, and thus the resources of multiple disciplines are required to address them. *Structure* showed the potential fruitfulness of conducting such multidisciplinary research on these problems, and the cognitive-historical method is one attempt to do so. Cognitive-historical analysis produces accounts of science that offer theories of the nature of the reasoning and representational practices employed by scientists, and of why they are effective, that can be subjected to empirical scrutiny. The outline presented here provides an indication of how specific cognitive-historical analyses both further and challenge Kuhn's insights into concept representation, learning, and concept formation.

Notes

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1. I emphasize "published" because in conversation with me and in transcripts of interviews conducted by Hanne Andersen, in March 1994 and October 1995, Kuhn did mention that cognitive psychological research into child development was figuring into the account he was writing in the follow-on book to *Structure* that he was still working on at the time of his death. He gave permission for the free use of the interviews after his death. Although his comments are sketchy, they do provide some pertinent remarks that will be discussed later in this essay.
2. Just what literature in cognitive science Kuhn was aware of and how deeply he had studied any of it is unknown. He did read the review of some of this literature presented in the extended Tech Report (Nersessian 1995a) and commented that he was "altogether sympathetic to [my] viewpoint" (personal correspondence, March 23, 1993). Further, he requested from me specific references in neuroscience, and we discussed his interest in the child development research of Susan Carey at MIT and others investigating the problem of whether one can determine what is innate ("hard-wired") through research into such developmental phenomena as when babies exhibit recognition of object permanence. The only recorded discussions I am aware of are the taped interviews with Hanne Andersen (see note 1). In these he mentions the neural net literature and the developmental literature as pertinent to his "perceptual space" notion and the need for a clear distinction between similar and dissimilar. He states his conviction that the Roschian "graded category structure" will fall out of the neurological case, if it can be made. He also mentions that at least a chapter of the follow-on book

would discuss the child developmental investigations. The book was incomplete at the time of his death and currently is being edited by John Haugeland and James Conant of the University of Chicago.

3. Nickles discusses the relations between the cognitive science notion of case-based reasoning and Kuhn's notion of problem exemplars (Nickles 1998). From a cognitive science perspective, the problem-solving success in case-based reasoning is linked to the *authentic* nature of the exemplary cases employed. A major problem with case-based reasoning is that cases are too specific and problems need to be very close to transfer. As a problem-solving method, it is inflexible in adaptation. In model-based reasoning, more is left unspecified, providing greater adaptability in creative problem solving.

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