
Cognitive Science and Science Education

Susan Carey

Massachusetts Institute of Technology

ABSTRACT: The quality of science education, like mathematics education, is a pervasive concern in educational improvement efforts. The cognitive orientation to the teaching of subject matter provides the context for Carey's discussion of science education. This orientation begins with the idea that to understand something, one must integrate it with already existing knowledge schemata. The paradox of science education is that its goal is to impart new schemata to replace the student's extant ideas, which differ from the scientific theories being taught. The resolution of this paradox sets the stage for current research in science education. Carey reviews studies that illustrate the extent of the mismatch between the student's schemata and the expert's schemata. She draws out their implications for instruction and for cognitive theories of learning. Several characterizations of the differences between naive and scientific explanations are contrasted: the view from the cognitive science literature on the novice-expert shift, from the history of science on theory change, and from science educators, as well as from the works of Piaget.

—The Editors

Many articles in this issue call for a minirevolution in education; indeed, they show that it is already under way, especially in the teaching of reading and writing (see Beck & Carpenter, this issue, pp. 1098–1105; Hayes & Flower, this issue, pp. 1106–1113). The key word in this revolution is *understanding*. The goal of reading is gaining understanding from texts; teaching reading, then, involves teaching techniques for gaining understanding and monitoring one's current understanding. This may hardly seem the stuff of revolution, but against the backdrop of concern with how to teach the mechanics of decoding texts (a still important goal in the early grades), the addition of this new emphasis and the demonstration that the techniques work even for young and poor readers are indeed revolutionary (e.g., see Palincsar & Brown, 1984).

Part of this shift of emphasis is due to the cognitive revolution within psychology, which provides a general account of what it *is* to understand a text. To understand some new piece of information is to relate it to a mentally represented schema, to integrate it with already existing knowledge. This may also seem self-evident, but a simple demonstration from over a decade ago might show the force of this idea. Try to make sense of the following text (from Bransford & Johnson, 1973):

If the balloons popped the sound wouldn't be able to carry since everything would be too far away from the correct floor. A closed window would also prevent the sound from carrying, since most buildings tend to be well insulated. Since the whole operation

depends on a steady flow of electricity, a break in the middle of the wire would also cause problems. Of course, the fellow could shout, but the human voice is not loud enough to carry that far. An additional problem is that a string could break on the instrument. Then there could be no accompaniment to the message. It is clear that the best situation would involve less distance. Then there would be fewer potential problems. With face to face contact, the least number of things could go wrong. (pp. 392–393).

If understanding of this passage eludes you, turn the page and look at Figure 1, a context that provides a key. Bransford and Johnson (1973) showed that subjects who were denied access to the context rated the text as fairly incomprehensible and, when asked to recall the text, remembered very little of it. Apparently, the figure allows access to a known schema (the serenade), which, in turn, provides a framework for comprehension. Simple demonstrations such as these set the stage for analyses of the schemata people have for understanding the world and for techniques that ensure that many different types of connections are made between what is being read and what is already known.

What does all this have to do with science education? Surely, understanding should also be at the core of the science curriculum. Our scientific heritage has provided us with deep and counterintuitive understanding of the physical, biological, and social worlds, and we want to teach at least some aspects of that understanding to youngsters. We also want them to grasp the nature of the scientific process, especially how it yields scientific understanding of the natural world.

The immediate lessons of the research on reading are clear. Students reading a science text or listening to a science teacher must gain understanding by relating what they are reading (hearing) to what they know, and this requires active, constructive work. This is the cognitive rationale (as opposed to the motivational rationale) for making science lessons relevant to students' concerns. But the serenade example is fundamentally misleading as applied to the problem of gaining understanding of a science text. In the case of science learning, students do not already have the schemata, such as the schema of the serenade, available to form the basis of their understanding.

We have arrived at a paradox: To understand text or spoken language, one must relate it to schemata for understanding the world. But the goal of science teaching is imparting new schemata for understanding, schemata not yet in the student's repertoire. So how is the student to understand the texts and lessons that impart the new information? This paradox is real, and failure to grasp

its full import is the source of many of the current problems in our science curriculum. It has been noted that junior and senior high school texts often introduce more new vocabulary per page than foreign language texts. But in foreign language texts the concepts denoted by the new words are already known to the student; that is, they already function in mentally represented schemata. But this is not so for new scientific vocabulary. Science as vocabulary lesson is a recipe for disaster, especially if understanding is the goal.

Indeed, the full force of students' *lack* of understanding of what they have been taught in science has just begun to be grasped. Phenomena independently discovered by cognitive scientists and by educational researchers dramatically demonstrate this lack.

The Phenomena of Misconceptions

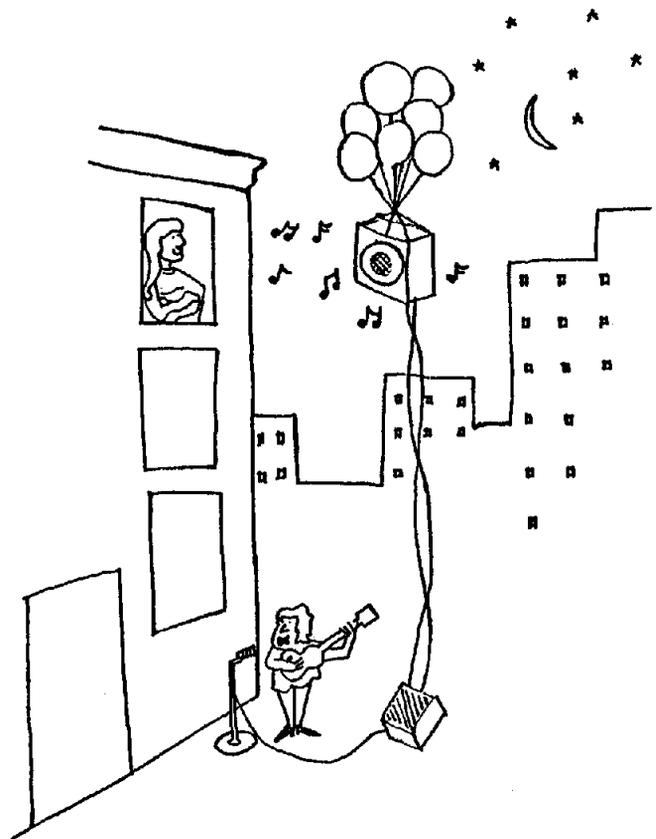
The phenomena I refer to are the misconceptions that prove so resistant to teaching. The diagnosis of misconceptions has become a highly productive cottage industry (see, e.g., the proceedings of the International Seminar on Misconceptions in Science and Mathematics, Helm & Novak, 1983). To illustrate the independent discovery of this phenomenon by educators and cognitive scientists, let me give two examples from mechanics. Remember your mechanics from high school or college physics? If you had no high school or college physics, see how you would answer the questions anyway, for your intuitions should be the same as those of the novices. If you had some physics but still have the novice intuitions, don't worry, that's part of the phenomenon of interest here.

Consider the problem in Figure 2, panel A. A coin is tossed; in Position a it is on the upward part of its trajectory and in Position b it is on the downward part of its trajectory. Your task is to indicate, with little arrows, the forces that are acting on the coin at Position a and at Position b. Novice physicists (even those who have had a year of college physics in which they have been taught the relevant part of Newtonian mechanics) draw the arrows as in panel B; experts draw the arrows as in panel C (Clement, 1982). The novices explain their two arrows at Position a as follows: There are two forces acting on the coin in its upward trajectory—the force imparted when it was thrown up and the force of gravity. The former force is greater in the upward trajectory; that's why the coin is going up. In the downward trajectory the force of gravity is the only force, or else it is the greater of the two, which is why the coin is descending.

Newtonians, in contrast, recognize only the force of gravity once the coin has been set in motion. Apparently, novices have a misconception about motion, one highly resistant to tuition, something like "no motion without a force causing it." This violates Newton's laws, which recognize a related conception: "no acceleration without a force causing it."

Correspondence concerning this article should be addressed to Susan Carey, Department of Psychology (E10-039N), Massachusetts Institute of Technology, Cambridge, MA 02139.

Figure 1
Context Sufficient to Make Sense of Balloons Passage

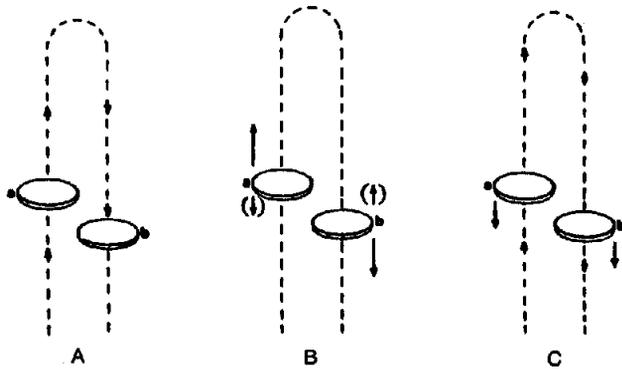


Note. Reprinted from "Consideration of Some Problems in Comprehension" (p. 394) by J. D. Bransford and M. K. Johnson. In *Visual Information Processing* by W. G. Chase (Ed.), 1973, New York: Academic Press. Copyright 1973 by Academic Press. Reprinted by permission.

Closely analogous misconceptions have been documented by other science educators, such as Viennot (1979), McDermott (1984), and Champagne and Klopfer (1984). Cognitive psychologists have also contributed to this documentation. For example, McCloskey (1983) described a slight variant of Clement's problem, with identical results. McCloskey also contributed several new cases of mechanics misconceptions. Consider the following problem. The subject is to imagine a ball going off a frictionless cliff at 50 mph and is to draw its trajectory as it falls to the ground. The correct answer is a parabolic trajectory (Figure 3, panel A), because the ball continues to travel horizontally at 50 mph but accelerates in its downward motion due to gravity (the only force acting on the ball). Most subjects draw a roughly parabolic curve, but some (about one fourth) draw curves such as those in panels B and C, in which there is a period of pure downward motion, sometimes following a period of pure horizontal motion (panel C). Subjects explain these trajectories by saying that the force causing the horizontal motion is dissipating and that gravity then takes over.

Analogous misconceptions are observed at other

Figure 2
 Problem (A), Novice Solution (B), and Expert Solution (C)

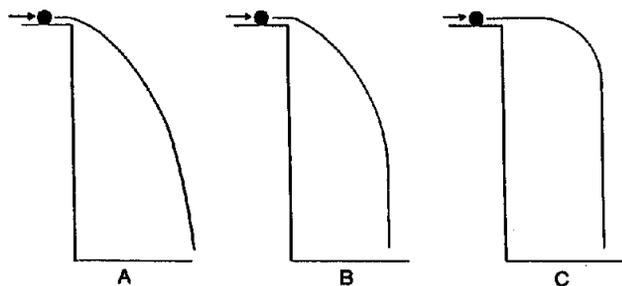


Note. Adapted from "Students' Preconceptions in Introductory Mechanics" by J. Clement, 1982, *American Journal of Physics*, 50(1), p. 68. Copyright 1982 by the American Association of Physics Teachers. Adapted by permission.

levels of the science curriculum. Johnson and Wellman (1982) documented that young children misconceive what the brain is for; they consider it the organ of mental life and thus deem it necessary for thinking, dreaming, remembering, solving problems, and so on, but deem it irrelevant to walking, breathing, sneezing, or even talking. One of the fifth grades in which Johnson and Wellman did their research had a two-week curricular unit on the brain, complete with a discussion of the autonomic as well as the central nervous system. Children who had completed this unit were just as likely to see the brain as irrelevant to breathing and sneezing as were those who had not yet had the unit.

Let me reemphasize that the mechanics misconceptions are also common *after* students have had relevant instruction (*two years* of physics—high school and college). The teachers in the courses whose students make these responses are surprised, even incredulous. The point

Figure 3
 Expert Solution (A) and Two Novice Solutions (B and C)



Note. Adapted from "Naive Theories of Motion" by M. McCloskey. In *Mental Models* by D. Gentner and A. Stevens (Eds.), 1983, Hillsdale, NJ: Lawrence Erlbaum Associates, Inc. Copyright 1983 by Lawrence Erlbaum Associates, Inc. Adapted by permission.

here is that these misconceptions document failure of the curriculum to impart the hoped-for understanding. But much deeper points can be made about the same phenomena.

Remember the paradox with which I began. Students, like anybody else, understand by relating incoming information to currently held knowledge schemata. Information presented in science lessons, even whole courses, is assimilated to existing knowledge structures, which differ in systematic ways from the knowledge structures the curriculum is intended to impart. Part of the paradox is resolved. Although students do not yet have the experts' mental schemata, they bring *some* schemata for understanding the physical, biological, and social worlds. This ensures *some* understanding of curricular materials. They are not in the position of readers of the serenade text, with no clues to any relevant schema for understanding the text or, worse, with no relevant schemata at all. But now we have another, much more difficult problem. *How* do the students' schemata differ from those of the experts? In the rest of this brief essay, I will discuss several proposals for how scientific schemata change in the course of acquiring more scientific knowledge. I hope to provide a feel for the complexity of the issues, to show that progress is being made, and to suggest that success will require the collaboration of cognitive scientists and science educators, who together must be aware of the understanding of science provided by both historians and philosophers of science. In my view, answering this question should be our top priority. The answer provides the instructional challenge—it tells us what changes our science curriculum must effect.

Knowledge Restructuring—the View From Cognitive Science

Cognitive scientists place the work on misconceptions in the context of other research on the so-called novice-expert shift. As the name implies, the novice-expert shift is the change that occurs as a beginner in some domain gains expertise. Many domains have been studied—most extensively, expertise at the game of chess and expertise in the physical sciences, particularly mechanics. Chi, Glaser, and Rees (1982) provided an excellent review of the cognitive science research on the novice-expert shift. As they pointed out, three methods have been brought to bear on the description of how novices differ from experts. The first (and most important) is the documentation of misconceptions, such as those sketched above. Other methods include analyses of perceived similarities among elements in the domain and information-processing analysis of how problems are solved.

Research by Chi and her colleagues illustrates the use of the second method. Novices and experts were asked to group physics problems according to similarity. Novices put together those problems that mentioned the same kinds of objects—problems about pulleys were grouped together, problems about inclined planes were grouped together, and so on. Experts, in contrast, placed together those problems solvable with Newton's laws of motion,

on the one hand, and those solvable using energy equations, on the other (Chi et al., 1982). These two ways of classifying the problems were orthogonal; inclined plane problems, for example, can be of both types. The expert apparently organizes his or her knowledge of physics in terms of abstract schemata not salient to the novice.

The force of this difference is brought home by studies using the third method: information-processing analyses of how problems are solved. Larkin and her co-workers (Larkin, McDermott, Simon, & Simon, 1980) showed that when solving mechanics problems, novices use painful means-end analyses, working with equations that they hope are relevant to the problem. Experts, in contrast, apply correct equations in a forward direction, indicating that they have a whole solution plan in place before they begin. The schemata in terms of which experts organize their knowledge of physics enable them to grasp the structure of problems in a way that novices cannot.

These first two methods discussed by Chi et al. (1982)—analyses of misconceptions, analyses of similarity judgments—have been used by science educators as well. Science educators have also developed the technique of “concept mapping,” in which the student and teacher, or the student and researcher, together produce a representation of the student’s concepts in the domain. This process serves both research and pedagogical goals. By comparing successive concept maps, produced as the student gains mastery of the domain, the researcher can see how knowledge is restructured in the course of acquisition. By participating in the production of maps for his or her own concepts, and monitoring how they change, the student sees what it is to gain understanding of a new domain.

All these techniques have as their goal the description of the novice’s (and expert’s) structuring of the domain, so that the two structures may be compared and the question of “restructuring” addressed. Chi et al. (1982) provided a precise statement of what might be meant by “restructuring.” First, experts represent relations among concepts different from the relations novices represent among them (as in the change from “no motion without a force” to “no acceleration without a force”). Second, patterns among these new relations motivate the creation of new, abstract concepts and schemata that are either not represented by novices at all or are not very accessible to them (as reflected in the changes in perceived similarity among physics problems and in the changes in the ways in which problems are attacked when solved). As Chi et al. (1982) put it, what is basic level for the novice is subordinate level for the expert.

So far, what I have said about the novice-expert shift suggests that the two systems share many concepts. Nodes corresponding to concepts such as *force*, *energy*, and so on, can be identified in both systems, and the terms for these concepts are identical or can easily be translated from one system to the other. Only if this is so may we conceive of the novice’s misconceptions as beliefs different from the expert’s about the same physical magnitudes or as the novice’s representing relations among the same concepts different from those of the expert. Only if this

is so may we credit novices with understanding when they manage to choose the correct equations, even in their bumbling way, to apply to a given problem. And only if this is so may we think of restructuring primarily as the building of more abstract schemata to incorporate the same subordinate schemata.

Knowledge Restructuring—the View From the History of Science

The study of conceptual change in the history of science has led to a much more radical view of restructuring of knowledge (Feyerabend, 1962; Kuhn, 1962; Toulmin, 1953). The original formulations of this radical view embraced a kind of meaning holism in which the meaning of each concept in a theory is determined by its relations with all other concepts in the theory. In this view, any theory change necessarily involves conceptual change. This view has other consequences: that successive theories are incommensurate and that each theory is unfalsifiable. These extreme formulations have been rejected by most philosophers of science (see Suppe, 1974, for extensive discussion), but a strong view of restructuring has survived, one that allows for true conceptual change among core concepts of successive theories (see Kuhn, 1982). In the strong view, successive conceptual systems differ in three related ways—in the domain of phenomena accounted for, in the nature of explanations deemed acceptable, and even in the individual concepts in the center of each system. These three types of differences sometimes result in one theory’s terms not even being translatable into the terms of the other (Kuhn, 1982). For example, in successive theories of mechanics each of the core terms, such as *force*, *velocity*, *time*, and *mass*, has fundamentally different meanings in the earlier as compared to the later theory.

As an example, consider the concepts *motion* and *velocity* in Aristotelian and Galilean mechanics. For Aristotle, motion included all change over time—movement, growth, decay, and so on. He distinguished two fundamentally different types of motion—natural and violent. His physics accounted for the two in quite different ways. Natural motions included objects falling to the earth, smoke rising, plants growing, and so on and were explained in terms of each kind’s natural place or state. Violent, or artificial, motions were those caused by an active agent, such as the movement of a person or the heat of a fire, and were explained in terms of entirely different mechanisms. Galileo, in contrast, restricted his study to movement through space, saw that the distinction between natural and violent motion was a distinction without a difference, and collapsed the two kinds of motion, bringing both into the domain of a single mechanical theory. Galileo’s system had no concept of natural place or natural state. Moreover, Aristotle did not distinguish between average velocity and instantaneous velocity—the key distinction that got Galileo’s kinematics off the ground (Kuhn, 1977). These changes at the level of individual concepts are the reason that the core terms of Aristotelian mechanics and Galilean mechanics are not

intertranslatable (Kuhn, 1982). The changes from Aristotelian to Galilean mechanics did not come easily. One cannot understand the process by which they occurred without considering the changes in the whole theory—in the domain of phenomena to be explained and in the kinds of explanations considered acceptable. All three kinds of change—in domain, concepts, and explanatory structure—come together. Change of one kind cannot be understood without reference to the changes of the other kinds.

I have contrasted two different senses of “restructuring.” The first, weaker sense is the one spelled out in Chi et al. (1982). With expertise, new relations among concepts are represented, and new schemata come into being that allow the solution of new problems and change the solutions to old problems. The second, stronger sense includes not only these kinds of change but also changes in the individual core concepts of the successive systems. The analysis of conceptual change is extremely difficult. I will not attempt to provide criteria for telling whether a particular case of restructuring involves this type of change. Nonetheless, consideration of clear examples such as the transition from Aristotelian to Galilean mechanics can help us decide other cases. In this transition several differentiations and coalescences occurred, which are both paradigm cases of conceptual change. Furthermore, the ontological commitments of the theories differ. Aristotle was committed to the existence of natural places and natural states, for these played a central explanatory role in his theory. According to Galileo’s theory, however, such things did not exist. These changes—differentiations, coalescences, changes in ontological commitments—are understandable only in terms of the changes in domains and causal notions between the successive theories. When all these changes are found, we should be confident that the knowledge reorganization in question is of the stronger kind, involving conceptual change.

The discussion of theory change by historians and philosophers of science poses a question for cognitive scientists. Does the novice–expert shift among adults involve conceptual change? There are certainly reasons to doubt it. Convincing examples in the history of science occur over years, even centuries, of conscious theory building by mature scientists. Nevertheless, recent work by students of the novice–expert shift begins to suggest that such restructuring does occur as individuals learn a new domain of science. Larkin (1983) proposed that novices think of physical causality in terms of time-based propagation of physical effects. In similar contexts experts explain phenomena in terms of state equations. Wisner and Carey (1983) documented a similar change in the historical development of thermal theories in the century between Galileo and Black. McCloskey and his colleagues (e.g., McCloskey, 1983) claimed that the beginner at mechanics brings a theory of mechanical phenomena to his or her study of mechanics in school and that this theory is identical to the pre-Galilean impetus theory of the Middle Ages. The misconceptions in Figures 2 and 3 are one source of evidence for this claim; the novice’s upward

force is the impetus imparted to the coin when it is tossed; it is horizontal impetus that maintains the horizontal trajectory after the ball has left the cliff. The reason that students’ misconceptions are so resistant to tuition is that learning mechanics requires a theory change of the sort achieved by Galileo—indeed, even more than that achieved by Galileo, all the way from impetus theory to Newton. If McCloskey is correct, strong restructuring involving conceptual change occurs, because many simultaneous adjustments at the level of individual concepts make the core notions of Newtonian mechanics unstatable in terms of the concepts of pre-Galilean impetus theory.

We are now in a position to understand the true importance of the study of student misconceptions. True, they show us the failure of our curricula. More important, they provide one clue as to the content of the student’s schemata for understanding nature and as to how those schemata differ from the expert’s. We cannot effect scientific understanding without grasping the depth and tenacity of the student’s preexisting knowledge.

The above examples of conceptual change in the course of learning scientific knowledge come from the high school and college curricula. In two recently published case studies of knowledge restructuring in childhood, my colleagues and I argued that cognitive development also involves conceptual change. Carey (1985b) analyzed the interrelated changes in the concepts of animal, person, plant, living thing, death, reproduction, gender, and so forth, in the years from age 4 to 10 and argued that these years witness the emergence of an intuitive biology as an independent domain of theorizing. The young child has not differentiated two senses of *not alive*—namely, *dead* and *inanimate*. At age 4, these concepts are embedded only in an intuitive psychology. Neither dead things nor inanimate things are capable of behavior, and biological relations such as parentage are seen as social relations. The misconceptions about the brain described by Johnson and Wellman (1982) should be seen in this context. Analogously, Smith, Carey, and Wisner (1986) documented the differentiation of *weight* and *density* over these same years and argued that the same analysis of differentiation that applies in historical cases (such as Black’s differentiation of *heat* and *temperature*, see Wisner & Carey, 1983) is required to describe this childhood case. The differentiation occurs in the context of developing an intuitive theory of matter. Piaget and Inhelder (1941) and Smith et al. (1986) documented many misconceptions in support of this claim. Young children think that sugar ceases to exist when it is dissolved in water; young children maintain that a small piece of styrofoam weighs nothing at all; young children think shadows are made out of some kind of stuff in the same sense that tables are, and so forth.

Knowledge Restructuring—the View From Science Education

Like cognitive scientists concerned with the novice–expert shift, most science educators have underestimated the de-

gree to which students' alternative conceptual frameworks differ from the science being taught. When misconceptions are cited, they are often given one-sentence characterizations, as in the following list taken from a recent review in *The Research Digest* (Capper, 1984, p. 4):

Examples of misconceptions include the following:

"Light from a candle goes further at night" (Stead & Osborne, 1980)

"Friction only occurs between moving surfaces" (Stead & Osborne, 1981)

"Electric current is used up in a light bulb" (Osborne, 1981)

"A worm is not an animal" (Bell, 1981)

"Force is a quantity in a moving object in the direction of motion" (Osborne & Gilbert, 1980)

"Gravity requires the presence of air" (Stead & Osborne, 1981; Minstrell, 1982)

Such a list seems to presuppose the weaker sense of restructuring (different relations among core concepts) because the misconceptions are characterized simply as false beliefs that are highly resistant to tuition. It is perfectly possible, of course, that the weaker sense of restructuring properly captures some of the above-cited mismatches between novice and expert conceptual systems. In another example, Champagne and Klopfer (1984) described studies showing that novices believe that heavier objects fall faster than lighter objects. This misconception truly may be a proposition stated over the same concepts as the expert's *faster* and *heavier*, such that the restructuring involved in attaining the expert conceptual framework does not require conceptual change.

In spite of this very real possibility, I doubt that weak restructuring characterizes most changes in conceptual frameworks achieved by successful science education. The source of my suspicion is the fifth misconception on the above list, "Force is a quantity in a moving object in the direction of motion." This is the "no motion without a force" misconception supported by demonstrations such as those depicted in Figures 2 and 3. But these are the very demonstrations that have been analyzed by McCloskey (1983) as part of an extensive alternative theory articulated in terms of concepts different from those of Newtonian physics. Science educators, as well, have challenged the simple false-belief characterization of the source of subjects' errors (e.g., McDermott, 1984):

The students' responses, both in word and action, indicated that they lacked a consistent conceptual system. Their use of the word "force" and other technical terms was ambiguous and unstable. . . . (It) could not be adequately summarized as a simple belief in the necessity of a force in the direction of motion. (p. 8)

Indeed, Viennot (1979) anticipated McCloskey's (1983) claims that the students' conceptual system resembles an evolved scheme of historical thought, "closer to the Impetus theory than to Aristotle" (Viennot, p. 213), and provided an elegant analysis of how some of the core concepts of the student differ from the core concepts of

Newtonian mechanics. Her central claim was that the student's concept of force conflates two distinct components, each called upon in different contexts. She dubbed the two components of the students' undifferentiated concept "force of interaction" and "supply of force," respectively. The former, force of interaction, is a function of the position of a moving body, and it determines the rate of change in velocity. Force of interaction satisfies the equation $F = ma$. It is appealed to whenever the problem calls forth a local analysis of the situation or when the force acts in the same direction as the motion. Thus students speak of "the force acting on the mass." Students speak of the latter, supply of force, as "the force of the mass" and think of it as the force in a body that keeps it moving. This is the notion appealed to when motion is made obvious in the statement of the problem and especially when the motion is in the opposite direction to the (true) resultant forces.

Viennot (1979) analyzed the relation of this undifferentiated concept of force to the concept of energy, noting that "energy" is sometimes used correctly and sometimes inextricably linked with the concept of force in a single undifferentiated explanatory concept. Besides being undifferentiated relative to the Newtonian concepts, the student's concepts differ from those of Newtonian concepts in other ways as well. Another key difference (also noted by Larkin, 1983) is that the students attribute physical quantities such as force and energy to the objects themselves, whereas the Newtonian system does not.

Viennot's analysis, then, complemented and extended that of the cognitive scientists who worked on the same misconceptions and provided a convincing example of conceptual change. It is very likely that other misconceptions also require conceptual change before being abandoned.

A Different Challenge to Weak Restructuring

McDermott (1984), quoted earlier, expressed dissatisfaction with the summary of the student's misconception as a simple belief in the necessity of a force in the direction of motion. I chose to explicate her dissatisfaction by presenting Viennot's (1979) analysis of the conceptual change involved, of the strong restructuring required to bring the novice and the expert into alignment. However, there is another thread of McDermott's dissatisfaction, one that denies the "alternative conceptual framework" approach altogether; in this interpretation, both weak and strong restructuring are denied. McDermott suggested that students lack a consistent conceptual system at all. Others have noted the inconsistencies in students' solutions to problems (e.g., White, 1981) and have wondered whether it is justifiable to credit students with "alternative conceptual frameworks" or "intuitive theories," rather than with bags of tricks that they call upon haphazardly.

One cannot deny the inconsistencies noted by the doubters. But inconsistency and apparent confusion are not sufficient to disprove the "alternative conceptual framework" picture of the learner. An intuitive theory is characterized by its core concepts, the phenomena in its

domain, and its explanatory notions. It is only with respect to its explanations of the phenomena in its domain that consistency is expected. It is easy to push any historical theory into inconsistency and its adherents into apparent confusion by probing at its periphery, rather than examining it at its core.

Whether the "alternative conceptual framework" position is correct is an empirical question. Its answer depends on finding a domain of phenomena consistently handled by the candidate intuitive theory. Carey (1985b) provided an analysis of at least one intuitive theory, the intuitive biological theory achieved by age 10. Carey also discussed the need for appeals to intuitive theories in cognitive science. We must appeal to intuitive theories to state constraints on induction, to explicate ontological commitments and causal notions, to analyze conceptual change, and so on. For these reasons, I cannot take seriously the denial of the "alternative conceptual framework" position.

A Different View of Restructuring—Piaget's

Thus far, we have been discussing how the student's conceptual frameworks for explaining natural phenomena differ from the expert's. Through this analysis we gain insight into the barriers students face to the understanding of newly presented scientific knowledge. Piaget gave us a quite different picture of the barriers to learning in young children. Piaget taught us that young children are fundamentally different kinds of thinkers and learners from adults—that they think in concrete terms, cannot represent concepts with the structure of scientific concepts, are limited in their inferential apparatus, and so forth. His stage theory described several general reorganizations of the child's conceptual machinery—the shift from sensorimotor to representational thought, from prelogical to early concrete logical thought, and finally to the formal thinking of adults. In Piaget's system, these shifts are domain independent. That is, they were meant to explain the child's limitations in learning new information with certain formal properties, no matter what domain of knowledge that information pertained to. Piaget's stage theory has come under fire and has been abandoned by many developmental psychologists. It is probably fundamentally misleading (see Carey, 1985a; Gelman & Baillargeon, 1983, for reviews). That is, many developmental psychologists now believe that the young child does *not* think differently from the adult, is *not* concrete, illogical, and so forth. Phenomena that were interpreted in terms of Piaget's stage theory are better interpreted in terms of specific alternative conceptual frameworks—novice-expert shifts and theory changes in particular domains.

The Piagetian work is closely related to that reviewed in this essay. Piaget and his colleagues have given us a rich stock of the misconceptions of young children. The nonconservations can be seen in this light, as can childhood animism, the child's beliefs about phase change and dissolving sugar, and so forth. Insofar as Piaget interpreted these misconceptions in terms of the child's changing

theories (as when conservation of weight, mass, and volume, the dissolving of sugar, the differentiation of weight and density, etc., were all interpreted in terms of the child's inventing a naive particulate theory of matter; see Piaget & Inhelder, 1941; Smith, Carey, & Wisner, 1986), his work was the direct forerunner to the research under discussion here. It is only when Piaget sought to further explain the differences between young children and adults in terms of domain-general limitations on the child's representational or computational abilities that his interpretations have come under fire. However, the question is still very much open. One goal of further research is to discover the relative roles of domain-specific and domain-general developmental changes in the description of cognitive development.

The Challenges

Some version of the "alternative conceptual framework" view is undoubtedly correct. I have argued that it is important to state the alternative versions clearly and to discover which are correct for which cases. I see two further challenges: the representational problem and the mechanism-of-change problem. First, we must find much better ways of *representing* conceptual structures so as to be able to analyze conceptual reorganization. Second, we must develop theories of what causes change.

Why Cognitive Scientists and Science Educators Need Each Other

The independent convergence on the same phenomena as central to the concerns of both groups sets the stage for successful collaboration between cognitive scientists and science educators. A second requirement for successful collaboration is complementary strengths—each group should bring something different to the collaboration. I believe this condition is met as well.

The representational problem will be solved, if at all, by cognitive scientists. Many are dissatisfied with current network representations of conceptual structures and are working on new formalisms for the representation of scientific knowledge. For example, Forbus and Gentner (1984) described a formalism for representing knowledge that models qualitative reasoning; most intuitive theories provide qualitative rather than quantitative explanations of natural phenomena. Cognitive scientists are also working on the relation of causal notions to the nature of human concepts (e.g., Murphy & Medin, 1985,) and on the analysis of ontological notions (e.g., Keil, 1979; Macnamara, 1982; Carey, 1985b). Such work will undoubtedly aid the joint enterprise of stating more precisely how knowledge is restructured in the course of acquisition.

The mechanism-of-change problem will be solved, if at all, by collaboration of the two groups. It is science educators who must test any ideas about how to effect knowledge restructuring in the classroom. In a recent article, Posner, Strike, Hewson, and Gertzog (1982) accepted the challenge of the "alternative conceptual framework" point of view and proposed instructional strategies that will effect knowledge reorganization. Much

more work along these lines is called for. Never again must ideas about knowledge acquisition be tested against cases that do not pose the difficult issue of its restructuring.

REFERENCES

- Beck, I. L., & Carpenter, P. A. (1986). Cognitive approaches to understanding reading: Implications for instructional practice. *American Psychologist, 41*, 1098-1105.
- Bell, B. F. (1981). When is an animal not an animal? *Journal of Biology Education, 15*(3), 213-218.
- Bransford, J. D., & Johnson, M. K. (1973). Considerations of some problems in comprehension. In W. G. Chase (Ed.), *Visual information processing*, (pp. 383-438). New York: Academic Press.
- Capper, J. (1984). Research in science education: A cognitive science perspective. In *The Research Digest*. (Washington, DC: Available from Center for Research Into Practice).
- Carey, S. (1985a). Are children fundamentally different thinkers than adults? In S. Chipman, J. Segal, & R. Glaser (Eds.), *Thinking and learning skills* (Vol. 2, pp. 485-518). Hillsdale, NJ: Erlbaum.
- Carey, S. (1985b). *Conceptual change in childhood*. Cambridge, MA: MIT Press.
- Champagne, A. B., & Klopfer, L. E. (1984). Research in science education: The cognitive psychology perspective. In D. Holdzkom & P. B. Ludz (Eds.), *Research within reach: Science education*. Washington, DC: National Science Teachers Association.
- Chi, M., Glaser, R., & Rees, E. (1982). Expertise in problem solving. In R. Sternberg (Ed.), *Advances in the psychology of human intelligence* (Vol. 1). Hillsdale, NJ: Erlbaum.
- Clement, J. (1982). Students' preconceptions in introductory mechanics. *American Journal of Physics, 50*(1), 66-71.
- Feyerabend, P. (1962). Explanation, reduction and empiricism. In H. Feigl & G. Maxwell (Eds.), *Minnesota studies in philosophy of science* (Vol. 3). Minneapolis: University of Minnesota Press.
- Forbus, K. D., & Gentner, D. (1984). *Learning physical domains: Towards a theoretical framework* (Report No. 5699). Cambridge, MA: Bolt, Beranek & Newman.
- Gelman, R., & Baillargeon, R. (1983). A review of some Piagetian concepts. In J. H. Flavell & E. M. Markman (Eds.), *Carmichael's manual of child psychology* (Vol. 3). New York: Wiley.
- Hayes, J. R., & Flower, L. S. (1986). Writing research and the writer. *American Psychologist, 41*, 1106-1113.
- Helm, H., & Novak, J. D. (1983). *Proceedings of the International Seminar on Misconceptions in Science & Mathematics*. Unpublished manuscript, Ithaca, NY.
- Johnson, C. N., & Wellman, H. M. (1982). Children's developing conceptions of the mind and the brain. *Child Development, 53*, 222-234.
- Keil, F. (1979). *Semantic and conceptual development: An ontological perspective*. Cambridge, MA: Harvard University Press.
- Kuhn, T. S. (1962). *The structure of scientific revolutions*. Chicago: University of Chicago Press.
- Kuhn, T. S. (1977). A function for thought experiments. In T. S. Kuhn (Ed.), *The essential tension*. Chicago: University of Chicago Press.
- Kuhn, T. S. (1982). Commensurability, comparability, communicability. In *Philosophy of Science Association 1982* (Vol. 2). East Lansing, MI: Philosophy of Science Association.
- Larkin, J. H. (1983). The role of problem representations in physics. In D. Gentner & A. Stevens (Eds.), *Mental models*. Hillsdale, NJ: Erlbaum.
- Larkin, J. H., McDermott, J., Simon, D. P., & Simon, H. A. (1980). Models of competence in solving physics problems. *Cognitive Science, 4*, 317-345.
- Macnamara, J. (1982). *Names for things*. Cambridge, MA: MIT Press.
- McCloskey, M. (1983). Naive theories of motion. In D. Gentner & A. Stevens (Eds.), *Mental models*. Hillsdale, NJ: Erlbaum.
- McDermott, L. C. (1984, July). Research on conceptual understanding in mechanics. *Physics Today*, pp. 1-10.
- Minstrell, J. (1982). Conceptual development research in the natural setting of a secondary school classroom. In H. B. Rowe (Ed.), *Science for the 80's*. Washington, DC: National Education Association.
- Murphy, G. L., & Medin, D. L. (1985). The role of theories in conceptual coherence. *Psychological Review, 92*(3), 289-316.
- Osborne, R. J. (1981). Children's ideas about electric current. *New Zealand Science Teachers, 29*, 12-19.
- Osborne, R. J., & Gilbert, J. K. (1980). A technique for exploring students' view of the world. *Physics Education, 15*(6), 376-379.
- Palincsar, A. S., & Brown, A. L. (1984). Reciprocal teaching of comprehension fostering and monitoring activities. *Cognition and Instruction, 1*(2), 117-175.
- Piaget, J., & Inhelder, B. (1941). *Le développement des quantités chez l'enfant* [The development of quantity in the child]. Neuchâtel, France: Delachaux et Niestlé.
- Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*, 211-227.
- Smith, C., Carey, S., & Wiser, M. (1986). On differentiation: A case study of the development of the concepts of size, weight, and density. *Cognition, 21*, 177-237.
- Stead, B. F., & Osborne, R. J. (1980). Exploring science students' concepts of light. *Australian Science Teachers Journal, 26*(3), 84-90.
- Stead, B. F., & Osborne, R. J. (1981). What is friction: Some children's ideas. *Australian Science Teachers Journal, 27*(3), 51-57.
- Suppe, F. (1974). *The structure of scientific theories*. Urbana: University of Illinois Press.
- Toulmin, S. (1953). *The philosophy of science: An introduction*. London: Hutchinson.
- Viennot, L. (1979). Spontaneous reasoning in elementary dynamics. *European Journal of Science Education, 1*, 205-221.
- White, B. (1981). *Designing computer games to facilitate learning*. Unpublished doctoral dissertation, Massachusetts Institute of Technology.
- Wiser, M., & Carey, S. (1983). When heat and temperature were one. In D. Gentner & A. Stevens (Eds.), *Mental models*. Hillsdale, NJ: Erlbaum.