Learning in Interactive Environments:
Prior Knowledge and New Experience

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This article summarizes research on the roles of prior knowledge in learning. Educators often focus on the ideas that they want their audience to have. But research has shown that a learner's prior knowledge often confounds an educator's best efforts to deliver ideas accurately. A large body of findings shows that learning proceeds primarily from prior knowledge, and only secondarily from the presented materials. Prior knowledge can be at odds with the presented material, and consequently, learners will distort presented material. Neglect of prior knowledge can result in the audience learning something opposed to the educator's intentions, no matter how well those intentions are executed in an exhibit, book, or lecture.

Consider a hypothetical book on wool production in Australia. Australian ranchers raise sheep in an extremely hot desert climate. The sheep are raised to have wool so thick that without yearly trimmings the sheep would be unable to walk. To many children, these facts together are absurd. Children think wool is hot; if you put a thermometer inside a wool sweater, the mercury would go up (Lewis, 1991). Wouldn't sheep grow more wool in cold places where they need to stay warm? Is wool hot because the sheep absorb the desert warmth?

Alternatively, consider a hypothetical exhibit on fish schooling. Fish follow each other in close formation that looks highly organized. But no single fish is the leader, and none of the fish know how to command the others. Many people assume that any organized system is the result of a centralized planner who directs the others. They think "there must be an older fish, who is smarter than the rest, and who leads the school. If marine biologists believe otherwise, well I guess its true, but I'll never be a marine biologist!"

Then again, consider a hypothetical lecture on jazz. Upon a first listening, one might hear the music as ugly, chaotic, and meaningless– "its just a lot of notes." Many years later, same music provides a rich and rewarding experience, and with more listening, yet more difficult music becomes accessible. How can you learn jazz if all you understand is classical music or pop?

To help people make the most of a new experience, educators need to understand how prior knowledge affects learning. To the child who does not yet understand heat and temperature, no quick explanation can possibly resolve the contradiction between the hot desert and the warm wool; it takes weeks to years for this understanding to emerge (Lewis, 1991). The adult who is unfamiliar with the possibilities of decentralized systems can't quickly be convinced that schooling fish have no leader (Resnick, 1992) — and instead they may be alienated from the setting. There is no way to give the first-time jazz listener the epiphany available to more practiced ears. Prior knowledge determines what we learn from experience.

Prior knowledge also forces a theoretical shift to viewing learning as "conceptual change." (Strike & Posner, 1985; West & Pines,1985). Previously learning was considered a process of accumulating information or experience. Prior knowledge is the bane of transmission-absorption models of learning. Mere absorption cannot account for the revolutionary changes in thought that must occur. The child simply can't absorb knowledge about wool, because prior knowledge about heat renders incoming ideas nonsensical. One can't assimilate fish schooling to a centralized mindset; distinct concepts for understanding decentralized systems must be developed. Jazz can't be translated into rock; one must cultivate ears for its unique organization.

On the other hand, it is impossible to learn without prior knowledge. Eliminating prior undertanding of heat won't explain why that sweater is still so nice in the winter, or how thick-coated sheep can be raised in the desert. The idea of decentralized systems must be built from some anchor in prior experience. It is easiest to appreciate unfamiliar music by starting with "crossover" artists who populate the periphery between jazz and rock or classical music.

The aspects of learning, prior knowledge and experience drawn out in these examples have a solid basis in research on learning. There is widespread agreement that prior knowledge influences learning, and that learners *construct* concepts from prior knowledge (Resnick, 1983; Glaserfeld, 1984). But there is much debate about how to use this fact to improve learning.

This article presents a set of research findings, theories, and empirical methods that can help the designer of interactive experiences work more effectively with the prior knowledge of their audience. It focuses on the central tension that dominates the debate about prior knowledge. This tension is between celebrating learners' constructive capabilities and bemoaning the inadequacy of their understanding. On one hand, educators rally to the slogan of constructivism: "create experiences that engage students in actively making sense of concepts *for themselves."* On the other hand, research tends to characterize prior knowledge as conflicting with the learning process, and thus tries to suppress, eradicate, or overcome its influence.

The juxtaposition of these points of view creates a paradox: how can students ideas be both “fundamentally flawed” and “a means for constructing knowledge?” The question cuts to the heart of constructivism: constructivism depends on continuity, because new knowledge is constructed from old. But how can students construct knowledge from their existing concepts if their existing concepts are flawed? Prior knowledge appears to be simultaneously necessary and problematic.This version of the learning paradox (Bereiter, 1985) is called the “paradox of continuity” (Roschelle, 1991). Smith, diSessa, and Roschelle (1993) argue that educational reforms must include strategies that might avoid, resolve, or overcome the paradox. Throughout the article, I endeavor to show how designers can work with prior knowledge despite its apparent flaws and without succumbing to an irresolvable contradiction. This requires careful consideration of assumptions about knowledge, experience, and learning.

The article is organized in three sections:

In the first section, I present findings both on how scientists learn, and on how students learn science. Evidence on scientific conceptual change leads to a recommendation to view science learning as refinement of everyday ideas, requiring a long time and in a rich social context. Consideration of how students learn science leads to additional recommendations: we should study successful learning, avoid interpreting prior knowledge in terms of dichotomies, see prior knowledge as providing flexible building blocks, and look for long-term transformations in the structure and coordination of knowledge.

The second section presents several major theoretical perspectives on the process of conceptual change. Piaget emphasizes changes in the structure of prior knowledge. His theory and methods suggest that designers create tasks that engage learners and create tension between assimilation and accommodation. Engagement in physical aspects of a challenging task can lead to reformulation of intellectual aspects of the task. Dewey emphasizes the conditions under which inquiry can resolve problematic experience. He suggests that designers discover that which is problematic for learners, and establish conditions that support the process of inquiry: time, talk, and tools. Vygotsky emphasizes the role of social process in learning, suggesting that new concepts appear first socially, and only gradually become psychological. He suggests that designers provide social models of appropriate activity, enable groups of learners to do more complex activities than they could handle individually, and use signs to enable people to negotiate the different meanings they find in social activity. Perspectives from information processing and situated learning theories are also briefly discussed in this section.

The third discussion summarizes some useful empirical methods. Successful design of interactive learning experiences builds on an understanding of how learners think. This requires using empirical methods to uncover prior knowledge. Traditional tests are written from the experts’ perspective, and label learners’ differences as “errors.” More modern and sophisticated methods allow educators to discover and work with the logic of learners’ reasoning. These methods include clinical interviews, think-aloud problem solving, and video interaction analysis.

Empirical Findings in Science and Mathematics Learning

Because prior knowledge is usually specific to a subject matter, it is difficult to state general facts about prior knowledge across all areas of human interest. Therefore, this article focuses on one area, science and mathematics learning, in order to provide a detailed example of prior knowledge at work.Prior knowledge has been studied more extensively in science and mathematics than in other areas. While the specific forms of prior knowledge in art or history may be different, we can expect that similar issues will arise.

Prior knowledge can be viewed from two perspectives, that of the accomplished scientist or, of that of the learner. Let’s start with the scientist.

Science as Refinement of Prior Knowledge

In this section we discuss the role that prior knowledge plays in thinking of accomplished scientists. I use the term “scientific knowledge” broadly here, refering both to“concepts,” and also scientists’ modes of perception, focus of attention, procedural skills, modes of reasoning, discourse practices, and beliefs about knowledge. It is conventional to think that scientific knowledge is different from everyday knowledge, and must replace everyday knowledge. But when we look more closely, it becomes apparent that scientists reuse metaphors and ideas drawn from prior knowledge. Moreover we see that this transformation occurs very gradually, and depends on the social practices of the scientific community. Only over long periods of time, and through extended conversations with their colleagues do scientist shape theories that are distinct from their commonsense roots.

The cartoonist presents the typical scientist as an Einstein scribbling mathematical formulae on a blackboard. Study of the scientific process reveals, however, that science does not always begin with mathematical abstractions nor empirical findings, but rather with ideas close to the surface of everyday knowledge. Einstein, for example, roots his own intellectual development not in mathematics, but rather in everyday ideas of rigidity, simultaneity, and measurement (Einstein, 1950; Wertheimer, 1982; Miller, 1986).

Einstein (1950) said that everyday knowledge provides a huge store of useful metaphors and ideas. From these, the scientist makes a free selection of a set of axioms, and thereupon begins constructing a theory. Einstein thought the origin of his theory might relate to a childlike exploration of space, and consulted with Piaget on the possible similarities between his personal intellectual development and that of children (Miller, 1986). In analyzing the work of other scientists, philosophers (Black, 1962; Kuhn 1970; Toulmin, 1972) and historians (Miller1986, Nercessian 1988) emphasize that science is a constructive activity. Its materials are drawn in part from the familiar images and metaphors of prior knowledge (Lightman, 1989, Miller, 1986).

If science draws upon everyday knowledge, why does scientific knowledge often appear so different from everyday knowledge, both in its form and content? In traditional accounts, philosophers searched for a Great Divide that separated scientific from everyday knowledge, much like the division between sacred and profane knowledge. If such a divorce could be made, scientific learning could be cut free of the biases of prior knowledge. These traditional accounts have not succeeded in establishing a firm divide between everyday and scientific knowledge.

An alternative to the Great Divide account comes from the work of sociologists, historians, and anthropologists who have studied scientific work (e.g. Latour, 1987; Knorr, 1981). From their inquiries, we learn that the properties of scientific knowledge arise from the social practices enacted by specific scientific communities. Discourse processes transforms prior knowledge into refined concepts that can be applied consistently by members of the scientific community. Scientific knowledge is not a *type* of knowledge, but rather a refined product, for which prior knowledge supplied the raw materials and social interaction supplied the tools.

The preceding discussion illustrates the contrast between replacement and re-use. New knowledge does not *replace* prior knowledge, rather new knowledge *re-uses* prior knowledge. Re-use is made possible by a process in which prior knowledge is refined, and placed in a more encompassing structure. The more encompassing structure comes in part from the social discourse norms that prevail within a community of practice.

The importance of time and social context become apparent when we consider how scientists learn. Kuhn (1970) argues that scientific knowledge does not always progress smoothly, but calls for "paradigm shifts" that involve large scale conceptual change. To invent Relativistic physics, Einstein had to depart from the very foundations of Newtonian science (Einstein, 1961). In paradigm shifts, the paradox of continuity again arises: how can scientists formulate a better theory if all they have is a flawed prior theory?

Analyzing conceptual change, Toulmin (1972) argues that conceptual change is not the mere replacement of one theory by another. Conceptual change occurs slowly, and involves a complex restructuring of prior knowledge to encompass new ideas, findings, and requirements. Thus Einstein does not merely replace Newton, he transforms Newtonian ideas and places them inside a new, encompassing analysis of space and time. Toulmin emphases that conceptual change, like normal science, is continual and incremental. It is mediated by physical tools, and regulated by social discourse. Only from the distant perspective of history does a paradigm shift appear as replacement. From a close-up perspective, conceptual change looks like variation and selection in a interrelated system of knowledge. Individual scientists vary the meaning of concepts and the use of methods. Given specific social rules and a long time over which to operate, selection can result in large scale changes in concepts.

From this analysis of the scientific process comes a series of important lesson for those who study learning: knowledge begins with the selection of ideas from everyday experience. The construction of scientific knowledge is a slow, continuous process of transformation taking place over a long period of time, involving successive approximation, and only gradually and incompletely becoming “different” from everyday knowledge.

In general, learning involves three different scales of changes. Most commonly, learners assimilate additional experience to their current theories and practices. Somewhat less frequently, an experience causes a small cognitive shock that leads the learner to put ideas together differently. Much more rarely, learners undertake major transformations of thought that affect everything from fundamental assumptions to their ways of seeing, conceiving, and talking about their experience. While rare, this third kind of change is most profound and highly valued.

These lessons have three implications for designers of interactive experiences. First, designers should seek to **refine prior knowledge**, and not attempt to replace learners’ understanding with their own. Second, designers must **anticipate a long-term learning process**, of which the short-term experience will form an incremental part. Third, designers must remember that **learning depends on social interaction**; conversations shape the form and content of the concepts that learners construct. Only part of specialized knowledge can exist explicitly as information; the rest must come from engagement in the practice of discourse of the community.

We next move to the viewpoint of learner. This will stress similar points, but draw attention to specific difficulties that arise in trying to interpret learners’ prior knowledge. First, we review data that shows the dominant the paradox of continuity in science education: science learners need prior knowledge, but prior knowledge seems to mislead them. Then we present a guidelines for resolving the paradox by reconsidering assumptions about learning. These guidelines may help educators interpret prior knowledge both in science and other areas.

Studies of Science Learning: Deepening the paradox

Studies of students’ prior knowledge in science and mathematics began in the 1970s and have since produced a voluminous literature (see reviews in Confrey, 1990; McDermott, 1984; Eylon & Linn, 1988). Interest in prior knowledge began with the careful documentation of common errors made by students in solving physics and mathematics problems. Analysis of interviews with these students reveals that the errors are not random slips, but rather derive from underlying concepts.

For example, when students are asked to explain a toss of a ball straight up in the air, they describe the motion in terms of an “initial upwards force” which slowly “dies out,” until it is “balanced” by gravity at the top of the trajectory. Physicists, in contrast, explain the ball toss in terms of a single constant force, gravity, which gradually changes the momentum of the ball: On its way upwards, the momentum is positive and decreasing; at the top, it is zero; and going down, the momentum is negative and increasing.

From analysis of students' thinking, researchers have determined that this "mistaken" explanation is not peculiar to this problem. Students commonly give explanations in terms of "imparting force," "dying out," and "balancing"(diSessa, 1993). From these commonsense ideas, students can generate endless explanations for different situations. In many cases, these explanations disagree with conventional Newtonian theory.

The text below examines the complex findings that have emerged from investigations of students' concepts. Notice that research tends to deepen the paradox of continuity: as we learn more about students' prior knowledge, the construction of scientific knowledge not only seems slow, but also seems increasingly improbable.

After they established the existence of prior concepts, researchers investigated the consequences of those concepts for subsequent learning. Most studies have looked at the role of prior knowledge in a conventional science course. The results depend on the nature of the task used to probe students' learning. If the task is procedural calculation, students can often learn to get the right answer independent of their prior knowledge. However, if the task requires students to make a prediction, give a qualitative explanation, or otherwise express their understanding, studies show that their prior knowledge "interferes. diSessa (1982), for instance, found students who were receiving an "A" grade in freshman physics at MIT, but could not explain the simple ball toss problem correctly. Using their prior knowledge, students often construct idiosyncratic, nonconforming understandings of the scientific concepts.

The prevalence of this effect has been widely documented. Halhoun and Hestenes (1985a & 1985b) found that 30% to 40% of physics students who pass freshman physics at various universities misunderstood the concepts. This also has been found at the elementary and secondary school levels, across both Western and non-Western cultures around the world. Indeed, some researchers suggest that 30% to 40% of physics teachers at the secondary school level misunderstand physics concepts because of their prior knowledge.

The processes by which "misconceptions" arise from a combination of prior knowledge and instructed subject matter are not unique to Newtonian mechanics. Children have concepts that differ from scientists in biology (Carey, 1985; Keil 1979), heat and temperature (Lewis, 1991; Wiser & Carey, 1983), electricity (Cohen, Eylon & Ganiel, 1983; Gentner & Gentner, 1983), mathematics (Resnick & Ford, 1981; VanLehn, 1989), probability (Shaughnessy, 1985), statistics (Tversky & Kahneman, 1983) and computer programming(Spohrer, Soloway, & Pope, 1989), and encounter difficulties as they interpret the scientific theories of these subjects. Furthermore, its not just children who produce mistaken interpretations by combining prior knowledge with instruction. Consider Tversky & Kahneman's (1982) findings about simple statistics. They have identified erroneous prior concepts about statistical phenomena that are widespread among professional psychologists — scientists who use statistics regularly. For example, both students and scientists suffer from “confirmation bias” that distorts experience to fit prior theory.

Prior knowledge exists not only at the level of “concepts,” but also at the levels of perception, focus of attention, procedural skills, modes of reasoning, and beliefs about knowledge. Trowbridge and McDermott (1980) studied perception of motion. Students perceive equal speed at the moment when two objects pass, whereas scientists observe a faster object passing a slower one. Anzai and Yokohama (1984), Larkin (1983), and Chi, Feltovich, and Glaser (1990) studied how students perceive physics problems and found they often notice superficial physical features, such as the presence of a rope, whereas scientists perceive theoretically-relevant features, such as the presence of a pivot point.Larkin, McDermott, Simon and Simon (1980) studied students’ solutions to standard physics problems and found that students often reason backwards from the goal towards the known facts, whereas scientists often proceed forward from the given facts to the desired unknown. Similarly, Kuhn (Kuhn,Amsel,& O’Loughlin, 1988) studied childrens’ reasoning at many ages and found that children only slowly develop the capability to coordinate evidence and theory in the way scientists do. Finally, Songer (1988) and Hammer (1991) studied students beliefs about the nature of scientific knowledge. They found that students sometimes have beliefs that foster attitudes antagonist to science learning.

In summary, prior knowledge comes in diverse forms. It affects how students interpret instruction. While it may not prevent them from carrying out procedures correctly, it frequently leads to unconventional and unacceptable explanations. Prior knowledge is active at levels ranging from perception to conception to beliefs about learning itself. Moreover, its effects are widespread through lay and professional population, from young children through to adults, and from low to high ability students.

Implications of Prior Knowledge: Learning as Conceptual Change

The overwhelming weight of the evidence has forced informed educators to fundamentally change the way science is taught. Learners are more likely to construct an interpretation that agrees with prior knowledge, and consequently disagrees with the viewpoint of the teacher. Thus, the effects of prior knowledge require a change from the view that learning is absorption of transmitted knowledge, to the view that learning is conceptual change (Resnick, 1983; Champagne, Gunstone, & Klopfer, 1985). Over time, learners need to accomplish the rarest form of change, a paradigm shift in their basic assumptions about the natural world, and the accompanying ways they see, conceive, and talk about the world. Conceptual change is a process of transition from ordinary ways of perceiving, directing attention, conceptualizing, reasoning, and justifying. Slowly learners transform prior knowledge to accommodate new scientific ideas (Posner, Strike, Hewson, & Gertzog, 1982).

Most of the data on science learning stresses *differences* between prior knowledge and scientific knowledge, rather than commonalities (Smith, et al, 1993). This has had an unfortunate consequence: rather than making education seem easier, it now appears to be impossible. Teachers get the impression that students *need* prior knowledge to learn new concepts, but prior knowledge *misleads* students to unconventional interpretations of concepts. Moreover, as the perception of a gap has increased, the metaphors used to describe the learning process have become more adversarial: prior knowledge must be confronted, challenged, overcome, replaced, eradicated, or destroyed in order for new knowledge to take its place. Educators celebrate students' constructive capabilities, and then roll out the heavy artillery to destroy it. The weight of the evidence makes paradox of continuity appear as a gaping void— there seems to be no bridge from prior knowledge to desired knowledge, with many apparent pitfalls along the way.

Undoing the Paradox of Continuity in Science Learning

Smith et al. (1993) recently investigated the paradox of continuity that arises in science education research. They suggest a interpretative theoretical framework that accepts the flawed character of some prior knowledge, but still gives it a positive role. The gist of their argument is that the paradox arises from implicit biases in theory and method. To undo the paradox, one must reconsider the implicit assumptions in science learning research.

First, one must recognize a bias in the data set. Almost all the data begins from identifying learning failure—examining a situation in which students make errors, and then identifying the concept that causes the error. If we start, on the other hand, by identifying success, and then investigating the concepts that enable success, we find an equally strong role for prior knowledge. Prior knowledge is properly understood not as a causes of errors or success, but rather as the raw material that conditions all learning.

Second, biases in research methodology tend to produce "attributes" of prior knowledge which might be better understood as "attributes of the learning task." For example, prior knowledge is said to be resistant to change by conventional instruction. Students might be resisting the learning experience, and not the knowledge. For example, most conventional science courses focus on manipulating mathematical expressions that refer to idealized situations, i.e. a frictionless plane. We should not expect such an abstract experiences to enable much change in familiar concepts of motion. When learning experiences are more concrete, related to familiar situations and interactive, "resistance" often disappears, and students construct new concepts quickly.Prior knowledge and conventional instructed knowledge may not be in conflict, but rather may be ships passing in the night.

Likewise, research methods that compare expert and novice performance tend to characterize their findings in dichotomies. For example, Larkin (1983) suggests that scientific knowledge is abstract, whereas prior knowledge is concrete. Other popular dichotomies are general vs. superficial, theoretical vs. familiar, and structural vs. superficial. A methodology based on dichotomies is well suited to sorting objects onto a bipolar spectrum, but is not well suited to analysis of how emergent wholes integrate pre-existing parts. For example, dichotomy-based methods mistakenly assert that science is abstract, and cannot identify how scientific knowledge successfully coordinates both concrete and abstract elements. A bias to dichotomies obscures the continuing roles prior knowledge plays in a more encompassing knowledge structures.

Third, one must be careful about the status that is attributed to prior knowledge. Researchers have termed prior knowledge "preconceptions." "alternative conceptions," "naive conceptions" "misconceptions" as well as "naive theories" and "alternative theories." Each term is loaded with theoretical connotations, that may be quite misleading and inaccurate, even if unintentionally so.

Terms that ascribe the status of a "theory" to prior knowledge are particularly misleading. For example, some researchers have drawn analogies between students ideas and historical theories, such as medieval impetus theory (McCloskey, 1983). However, children are not "short scientists" nor are ordinary adults "medieval scientists." All people, including scientists, build knowledge from a pool of familiar metaphors like "balancing" and "dying out." This pool of metaphors is not structured like a theory; it is not necessarily consistent, complete, or deductively sound. Rather it is a loose aggregate of useful ideas that can be flexibly applied. Although children and ordinary adults sometimes produce explanations that sound like medieval theory, they do necessarily hold their knowledge in the same regard that a scientist holds a theory.

Terms that focus on the mistaken or alternative status of prior knowledge are also misleading. Prior knowledge can produce mistakes, but it also can produce correct insights. Sometimes the same element of prior knowledge can provide both an incorrect alternative to one theory and be a component of a correct theory in another topic area. For example, consider the common idea of "force as a mover," which holds that an applied force results in a proportional velocity (diSessa, 1983). This is often misapplied to situation in which a constant force acts on a frictionless object. Conventional electromagnetism texts, however, assert that "an electron moves with a velocity proportional to the applied electromotive force." Thus "force as a mover," can be either a misconception or a sanctioned modelling concept, depending on the context of use. The consequence of such observations is that educators should treat prior knowledge as a store of generative metaphors, not a collection of wrong theories. Prior knowledge is like a set of building blocks, and not like an enemy fortress.

Fourth, one must beware of a reductionist bias in theorizing about prior knowledge. In general, research has focused on identifying a very small number of knowledge elements and attributing great power to each. Studies of science learning, to the contrary, remind us is that scientific thinking is comprised of many diverse components.Learning can occur by recontextualizing, re-prioritizing, or refining the parts. For example, many "misconceptions" are correct elements of knowledge which have been overgeneralized. By specifying a narrower range of situations, the concepts become "correct." In mathematics, for instance, students often have the misconception that the x-intercept of a line is equal to the inverse of the "b" term in equations of the the form "$y = mx + b$." This concept is correct, but only in the case where the slope of the line is 1 (Moschkovich, 1992). One step in refining knowledge is adjusting the context in which the knowledge is applicable.

Similarly, as students learn science, knowledge elements change in priority (diSessa, 1993). For example, we ordinarily think of surfaces as rigid. To understand the normal force, however, we must lower the priority of rigidity and raise the priority of springiness. In analyzing a book on a table, for instance, the scientist sees a heavy object compressing the surface of the table slightly, giving rise to a restoring force upwards. Thus the scientist, while understanding that books and tables are mostly rigid, gives a higher priority to springiness. Both springiness and rigidity are commonsense concepts; to accommodate Newtonian theory, only their relative priority shifts.

Likewise, Roschelle (1991) investigated how students develop a concept of vector addition suitable for understanding acceleration. Relevant prior knowledge for vector addition includes a commonsensical notion of addition, as well as concepts of pulling, guiding, and hinging. Through concrete experience over time, students form a synthetic vector addition concept that draws upon these initial metaphors, but is considerably more precise and specific. According to diSessa (1993), science learning involves many such shifts in generality, priority, and refinement. The net result is the transformation of a loose aggregate of knowledge into a crystalline structure of well-established priorities, tuned to the demands of conventional scientific theory.

In summary, we see that students quickly acquiring many different kinds of knowledge, but only slowly acquire the ability to coordinate and integrate these different sources of understanding. Students can learn to calculate from mathematical formulas, and can learn to give qualitative explanations but it takes a long time to acquire to the ability to coordinate qualitative explanations with mathematical formulas that represent a theory.

In the previous section on scientists use of prior knowledge, it was emphasized that knowledge changes slowly by restructuring, not replacement. This is equally true for science students. Moreover, to overcome the paradox of continuity for science learning, we should attend to several guidelines for interpreting prior knowledge:

- Study success, not just failure, and identify how prior knowledge enables success.
- Use methods that allow observations of students constructing integrated wholes, not just shifting valences on a bipolar scale.
- Be wary of viewing prior knowledge as an enemy fortresses that is wrong, alternative, or theoretical in character, and instead see prior knowledge as a disorganized collection of building blocks.
- Expect learning to occur through gradual refinement and restructuring of small component capabilities in a large, distributed system, with increasing coordination.

To the list discussed above, I would add that theories of prior knowledge tend to have an individualistic and psychological bias. This bias is partially reflecting in the selection of “concepts” as a focus of study. On every occasion of concept use, however, a learner is in a social and physical situation; these situations powerfully effect the learning that takes place (Roschelle & Clancey, 1992).

Educational experiments that work with prior knowledge have realized considerable success in provoking and supporting conceptual change. Clement, Brown & Zeitsman (1989) have developed a science curriculum based on “anchoring analogies” — everyday concepts from which scientific concepts can grow. Similarly, Minstrel (1989) has developed classroom techniques for gradually restructuring students conceptions. White (1993) has developed a computer-based curriculum called “ThinkerTools” which develops a scientific concept of motion gradually over several months. White’s curriculum include explicit attention to differences between scientific discourse and ordinary discourse (e.g. the meaning of “law”), and organizes a social context that more closely resembles the collegial environment of scientific work than the authoritarian classroom. Roschelle (1991) studied students’ learning from similar computer software and concluded that students learn the scientific concept of acceleration through a series of gradual transformations of their prior knowledge.

In reviewing teaching methods that work, Scott, Asoko, and Driver (1991) note two successful strategies, one based on explicitly working with conflicts, and the other based on building on correct prior knowledge. In any educational situation, there is likely to be some conflict, and some extensions to prior knowledge. Learners can succeed in conceptual change as long as appropriate care is taken in acknowledging students ideas, embedding them in an appropriate socially discourse, and providing ample support for the cognitive struggles that will occur.

In summarizing the broad sweep of research, perhaps the most important lessons are these. First, we must give up the notion of transmitting knowledge to absorbent minds; learning is a process of **conceptual change**. Second, conceptual change is a **slow, transformative** process. Rather than rejecting prior knowledge and accepting instructed knowledge, learners must gradually refine and restructure their prior knowledge. Third, to overcome the paradox of continuity, we should study success, avoid dichotomy-based empirical methods, see prior knowledge as providing building blocks, look for learning as long-term transformation knowledge into larger, more systematically coordinated wholes.

Prior Knowledge in Theories of Learning

Research in science and mathematics learning has not yet produced a successful theory of learning, nor are theories available in other subjects. The current state of the art, as described above, merely suggests a set of framing assumptions that dissolve the paradox of continuity sufficiently to allow education to proceed.

But how does knowledge change and grow? To answer this question, we must turn to more general theories of learning.Philosophically, the issue of prior knowledge arises in Epistemology, the study of justified true belief (Edwards, 1967) Kant was concerned with identifying certain knowledge. He distinguished between “a prior” and “a posteriori” knowledge. “A prior” schemata consist of basic structures that enable us to detect regularities in the environment. Space and time were Kant’s primary candidates for “a priori” status. Most other knowledge comes from synthetic combination of schemata with experience.

Most theories of conceptual change stick with this framework of “a priori” structures combining synthetically with new experience, though they vary the notions of schemata, experience, and the construction process in which schemata and experience come together. They also differ in emphasis: Piaget emphasizes psychological changes to schemata, Dewey emphasizes the transformative possibilities in experience, and Vygotsky emphasizes the role of social interaction in reconstructing the relationship of structures to experience. In the few short pages available here present a quick tour of how these theories treat the issue of prior knowledge.

Piaget: Developmental Growth of Schemata

Piaget’s theory (Inhelder & Piaget, 1958; Ginsburg & Opper 1979; Gruber & Voneche, 1979) concerns the development of schemata in relation to new experience. Children, like adults, combine prior schemata with experience. However, children’s notions of space and time qualitatively differ from adults’ (Piaget, 1970) [1]. Piaget provides a theory of conceptual change that focuses on the development of schemata from childhood to maturity.

Piaget provides a characterization of children’s knowledge at four stages of maturity, termed sensi-motor, preoperational, concrete operational, and formal operational (Corsini, 1994). At each successive stage, more encompassing structures become available to children to make sense of experience. For example, Piaget demonstrates that children cannot perform controlled experiments with variables, or reason with ratios, before the formal operational stage. Prior knowledge, in the form of structural schemata, thus play a determining role in how children make sense of interactive experience.

In Piaget’s account of conceptual change, knowledge grows by reformulation. Piaget identifies a set of invariant change functions, which are innate, universal, and age independent. These are assimilation, accommodation, and equilibration. Assimilation increases knowledge while preserving of structure, by integrating information into existing schemata. Accommodation increases knowledge by modifying structure to account for new experience. For Piaget, the critical episodes in learning occur when a tension arises between assimilation and accommodation, and neither mechanism can succeed on its own. Equilibration coordinates assimilation and accommodation, allowing the learner to craft a new, more coherent balance between schemata and sensory evidence. Reformulation does not replace prior

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[1] Piaget thus undercut Kant’s position that one couldn’t reason without certain prior concepts of space and time. Children have different concepts that Kant assumed, but can reason nonetheless. Piaget showed that very fundamental elements of reasoning develop as children mature. Einstein similarly showed that fundamental concepts of space and time also must change for physics to mature. Piaget and Einstein thus substantially extend the consideration of what changes in conceptual change; children and scientists alter the very foundations of what they know. Of course, such broad changes occur very slowly.

knowledge, but rather differentiates and integrates prior knowledge into a more coherent whole.

Piaget influences educators not only by his theory, but also by his method. He spent long hours coming to know children's modes of thinking (using the clinical interview, discussed later). After Piaget, we must assume that children will make sense of experience using their own schemata. Yet, we also must carefully interview children, seeking an understanding of their form of coherence. Most followers of Piaget are constructivists who cultivate a deep appreciation of children's sense-making, and design interactive experiences accordingly.

Piaget generated many innovative task-settings in which children become involved in active manipulation of physical objects. Trying to achieve a goal in physical task can promote conflict between assimilation and accommodation in the accompanying psychological task. Moreover, alternative physical actions can suggest different conceptual operations, and thus opportunities that arise in physical activity can inspire mental restructuring. Using these insights, Kuhn et al. (1988) shows that children can learn to coordinate theory and evidence in a period of several weeks if provided with engaging, playful, thought-provoking tasks. Harel & Papert (1991) extend this point by suggesting that the best tasks for constructing ideas are those in which children have to build something that works. While "construction" and "constructivism" are not necessarily linked, they go well together. Dewey's theory, discussed in the next section, also identifies designing, making, and tinkering real things as critical to conceptual change.

In summary, Piaget suggests that learners overcome the paradox of continuity with the help of slow, maturational processes that operate when doing a task provokes conflict between accommodation and assimilation, and support for equilibration between these. He suggests that designers of interactive experiences invest the empirical effort needed to appreciate learner's perspective. From an understanding of this perspective, one can design tasks that are likely both to attract learners, to provoke disequilibration, and to support the necessary but difficult work of knowledge reformulation. Tasks should be simple and direct, with individual concrete operations mapping closely to the conceptual operations at stake. Experience in which learners construct a working physical arrangement are often powerful for constructing knowledge; for example, the best way to progress past your prior understanding of a painting might be to try to paint one like it.

Dewey: The Conditions for Reflective Experience

Whereas Piaget develops a theory of the growth of structuring schemata, Dewey elaborates the experiential side of learning (Dewey, 1938b). Piaget exposes Kant's "a priori" structures as genetic variants, not fixed truths. Dewey exposes the problematic nature of experience, which is not "given" to us either, but rather is created in our transactions with nature and with each other, and thus is dependent on the prior knowledge that we bring to it.

In Dewey's account of learning (Dewey, 1916; Dewey, 1938a; McDermott 1981), problematic experience comes to the fore. For Dewey, primordial experience occurs in a physical and social situation. Moreover, learners are not “in” a situation like paint is “in” a bucket; rather experience is an active transaction that coordinates doing and undergoing (Dewey, 1938b). Even in watching a painting, we actively direct our gaze, and undergo a transformation of our field of vision. Experiential transactions have simple qualities that we can directly apprehend; e.g., they can be joyful, frightening, tasty, or harmonious.

In most of life, we proceed smoothly from one transaction to the next, using and enjoying the objects of our experience. But sometimes, experience has the quality of being problematic. By this Dewey means that we feel confused, uncertain, incoherent, unable to act. We are unable to coordinate prior knowledge and prior habit to cope with the exigencies of the moment. In the situation of problematic experience, we can engage a different mode of life from use and enjoying, which Dewey calls *inquiry.*

Inquiry (Dewey, 1938a).is the reflective transformation of perception, thought, and action, re-unifies experience into a more satisfactory whole.The process of inquiry involves reflection on experience; we apply tools like concepts, drawings, and gestures to point to features of experience that are troublesome. At the same time, we apply tools to project possible solutions. Through experiment and reflection, both schemata and perception are slowly transformed to bring coherence, coordination, and meaning to our transactions.

Inquiry involves psychological, physical, and social interaction. Schön (1979) gives a good example. A team of engineers was trying to design a synthetic paint brush, but the paint would not go on smoothly. One engineer decided to look very carefully at how a bristle brush works. As he slowly painted, the others watched. Slowly they saw that the real brush was not like a sponge. Metaphors of “pumping” and “channeling” came into discussion to describe how paint flowed smoothly down the bristles. Over time, the engineers transformed their notion of painting from absorbing paint, to pumping and channeling paint. This enabled them to design a successful synthetic brush.

In this example, we see how a problematic experience involves prior knowledge. Prior knowledge was invoked both in creating the original problematic (seeing a brush as releasing paint) and the new understanding (metaphors of pumping and channeling). The process of inquiry involves psychological, social, and physical interaction that gradually enabled the engineers to transform their puzzlement into a new understanding.

Dewey is often viewed as a child-centered educator, who emphasized growth of the child’s interest and capabilities over the mandates of a curriculum. However, Dewey took pains to oppose any attempt to place a child’s prior knowledge and a curriculum’s desired knowledge in conflict or dichotomy (Dewey, 1938b). We should neither champion children’s native desires over the hard-earned wisdom of disciplines, nor static views into children’s minds. Dewey urged a view of children’s knowledge as fluid, flexible, generative, and unformed. By designing appropriate experiences, an educator should be able to move from children’s interest and capabilities towards the more stable, definite, and structured content of organized subject matters. Thus an educators responsibility is both to enable the child to engage in inquiry, and to guide inquiry so it leads towards broader participation in the culture the child is to enter.

Dewey's life work was concerned with understanding the conditions that enable inquiry to proceed, and herein lies the most salient inspiration for designers of interactive experiences. The key lesson is this: Attend to that which is problematic in an experiential transaction, *from the point of view of the learner,*and allow time and space for inquiry to occur as an activity in its own right. A secondary concern is provide tools that enable inquiry to be effective. Inquiry occurs not in the head, but in direct engagement with the world and with others. To succeed, learners need ways to sketch and explore ideas and phenomena, and to test alternatives experimentally. Moreover, language (which Dewey calls the "tool of tools") can be an invaluable means for re-describing, re-orienting, and restructuring experience. Attempts to coordinate one person's understanding with another gradually shifts idiosyncratic ideas towards a common ground. Thus educators interested in working with children's prior knowledge, should look for situations in which that prior knowledge becomes problematic, and should create three conditions that enable inquiry to proceed successful: time, tools, and talk.

Dewey overcomes the paradox of continuity by focusing on the nature of experience. Under the right conditions, a learner engaged with a problematic experience can effect a transformation of prior knowledge. This transformation restructures thought, perception, and action elements into a more integrated, coherent whole. Over a long time, with careful guidance, the net result of many local transformations can be an overall set of ideas and practices approximates the central core of an organized subject matter.

Vygotsky: Social Reconstruction of Prior Knowledge

Vygotsky developed his work partially in response to Piaget's neglect of social interaction. Whereas Piaget emphasizes the maturation of schemata within the individual, Vygotsky(1986) argued that advanced concepts appear first in social interaction, and only gradually become accessible to an individual. Thus Vygotsky primarily elaborated the role of social interaction in transformation of prior knowledge.

In one of his studies, Vygotsky (1986) specifically examined the role of prior knowledge is science learning. He argued that children have spontaneous concepts and scientific concepts, and that these are not in conflict, but rather are part of a unitary process. In this process, Vygotsky sees spontaneous concepts growing upwards in generality, preparing the ground for more systematic reasoning. Simultaneously scientific concepts, which are introduced by instruction, grow downwards to organize and utilize the spontaneous concepts. Upon achieving a through and systematic intertwining, the learner gains both the power of the abstract (maximum substitutability) and of the concrete (maximum applicability).

The restructuring process that the intertwines spontaneous and specialized concepts occurs in social interaction, and is mediated by sign systems, such as language and drawing. Whereas Piaget focuses on disequilibrium among schemata, and Dewey focuses on problematic experiences, Vygotsky turns our attention to the "Zone of Promixal Development (ZPD)" (Wertsch, 1985; Newman, Griffith, & Cole, 1989). The ZPD is formed by the difference between what a child can do without help and the capabilities of the child in interaction with others. In this construction zone, the child can participate in cultural practices slightly above his or her own individual capability. Successful participation can lead to internalization. In Vygotsky's account, the primary resources for restructuring prior knowledge come from culture. Moreover, the restructuring process itself occurs externally, in social discourse. Children share, negotiate and try out meanings in social experience, and adults can shape those meanings by bringing them into the framework of cultural practice.

Recent translations of Vygotsky have inspired designers of interactive experience in several ways. First, the concept of the ZPD suggests that designers provide "scaffolding" to enable learners to participate in a more complex discourse than they could handle on their own (Brown & Ferrara, 1985). This scaffolding can be in the form of social processes that manage some of the complexity of a task for learners, allowing them to participate while focusing only on one aspect. In addition, educators can engage in "cognitive modeling" whereby they act out and verbalize a reasoning process that usually occurs only in an expert's head (Palinscar & Brown, 1984). Thus learners can acquire reasoning practices by imitation and apprenticeship (Collins, Brown, & Newman, 1989; Rogoff, 1990). Finally, Vygotsky inspires designers to create "mediational means" that enable learners to negotiate the meaning of a concept verbally (Hickman, 1985). Meditional means can be a graphic notation system or a set of linguistic conventions that extend students ability to talk about and act upon the relation between their understanding and another person's understanding.

Like the other theorists, Vygotsky overcomes the paradox of continuity by suggesting that learning coordinates spontaneous and specialized concepts in a gradual transformative process. Unlike Piaget's maturational account, Vygotsky sees structure coming from culture and gradually expanding into individuals psychological repertoire through social interaction in the ZPD. By scaffolding, modelling, and negotiating, experienced adults are able to guide learning so as to bring the learner into a specialized cultural community.

Information Processing and Situated Learning

Piaget, Dewey, and Vygotsky each developed their theories in the first half of the 20th century. In the second half of the century, information processing views have dominated, only recently to be challenged by a loosely coupled set of ideas called "situated cognition." We briefly survey the additional resources that these advances contribute to an understanding of prior knowledge.

Information processing psychology builds on the metaphor of mind as a computer of symbolic data

(Newell & Simon, 1972; Posner, 1989). Successful information processing (IP) models utilize mechanisms similar to those described by Piaget: accommodation modifies a schema, or assimilation modifies data to fit an existing schema. However, IP modeling has worked best in areas where prior knowledge is weakest— in rule-dominated logic and gaming tasks. Modeling learning in areas were commonsense is rich has proven to be an immense task. Moreover, the analogy between minds and computers quickly breaks down where prior knowledge is concerned: you can reprogram a computer, completely replacing its existing program with a different one, whereas human minds must make new knowledge from old. Likewise, computer models have impoverished capabilities for experience and social interaction.

To those interested in prior knowledge and learning, the major contribution of IP is the production of innovative representational systems and sound scientific methodology for analyzing learning processes. The relevant methodological contributions of IP are briefly summarized later in this paper. The representations can help in two ways. First, they can make it easier to describe prior knowledge precisely. For example, VanLehn (1989) showed how the concepts underlying mistakes in addition problems could be given a precise description. From this specific diagnosis, a teacher could provide more focused instruction. Second, representations can be a tool that allows the learner to reflect. For example, children can use "semantic networks" to map the associations among ideas before, during and after learning. Likewise, tree diagrams can help students understand processes that are hierarchically composed rather than linearly composed, such as the generation of a geometric proof (Koedinger & Anderson, 1990). Providing a tool for representing prior knowledge can enable learners to reflect more systematically on prior knowledge.

Situated Learning (Brown, Collins, & Duguid, 1989; Lave, 1988) has emerged in the last decade as a critique of IP's focus on internal schemata and neglect of physical and social context. Situated learning, like Deweyian theory, holds that all learning occurs within experiential transactions— coordinations between personal agency and environmental structures. Like Vygotsky, situated learning also emphasis the social construction of knowledge. Most striking in relation to the IP accounts, is the overall conception of learning as *enculturation.* In place of relations between schemata and experience, situated accounts focus on learning in terms of relations between people, physical materials, and cultural communities (Lave & Wenger, 1989). Knowledge is developed, shared, and passed on to the next generation by local communities that maintain a particular discourse or work practice, such as a craft guild or academic discipline. Growing ability *to participate* in a community-based culture has precedence over the ability *to know.* In fact, situated learning has relatively little to say about "prior knowledge" as such, but focuses instead on how ordinary work and discourse practices can become specialized, and how identities develop.

In its present (and quickly evolving) state, situated learning offers a constructive critique of Kantian-derived conceptions of learning. First, it reminds us that knowledge and social identity are tightly intertwined. A person's prior knowledge is part of his or her personal identity in society. Conceptual change almost always involves a transformation of identity— the specialization of concepts about motion not only enables a child to think more like a scientist, but also allows a child to progress towards becoming a scientist. *Becoming a participant* in a community can be a stronger motivation the *gaining knowledge* This is a useful corrective to educators who focus on the "right knowledge" and forget to ask who a learner is becoming.

Lave and Wenger (1989) offer the notion of "legitimate peripheral participation" (LPP) to make this more precise. LPP suggests that "becoming " requires participation in the activities of a community. However, learners often cannot participate in the core activities of a specialized group, e.g. an ordinary person cannot join a scientific laboratory. Thus learning often occurs on the periphery of the community, in specialized places that have been legitimized as entry points. Museums, schools, and clubs (e.g. 4H) can serve this purpose. LPP guides us to develop interactive experiences that form part of a legitimate trajectory towards full membership in a specialized cultural community. Because transformation of identity and conceptual change both operate gradually over a long period of time, it is important to specify an overall trajectory that could enable a learner to move from the periphery to the core of a community.

At the cutting edge of current work on prior knowledge, we find researchers concerned with the mutual interaction of social discourse practices with constructive, participatory experiences.

How to Investigate Prior Knowledge

Due to the pervasive influence of prior knowledge on learning, good designers of interactive experiences need to cultivate a sensitivity to the different points of view that learners will bring to an experience. This sensitivity is best gained by first hand experience with other's points of view; no description in the literature can fully convey the character and constitution of a learners' prior knowledge. Fortunately, becoming sensitive to prior knowledge is not hard to do. One must simply look and listen closely as learners use your materials. When something strange and incomprehensible occurs, don't give in to temptation to brush it aside; take the occurrence as opportunity to learn.

Understanding prior knowledge is 90% perspiration and 10% method. Standard tests are useless, because they are almost always written from the perspective of the expert. Instead, it is crucial to get learners to talk and then to pay careful attention to what they say and do. Three specific methods from research community can be helpful:

Piaget developed the clinical interview as a method for investigating children's sense-making. A clinical interview (Posner & Gertzog, 1982; White, 1985;) usually involves a task in which the learner manipulates some physical materials. Good tasks are simple and focus tightly on the concept at stake. Thus, a strange set of actions in the task readily indicates a different sensibility. The interviewer then probes the learner's understanding by asking questions about things the learner has said or done and avoiding leading questions. As the interview progresses, it is often helpful to ask the learner to consider alternatives to see how stable a particular concept is. A transcript of the resulting interview provides a great deal of detail about prior knowledge.

Researchers in information processing theory have developed the technique of the think-aloud protocol (Ericsson & Simon, 1984; Simon & Kaplan, 1989), which collects information about a learner's problem solving process.The learner is trained to "think aloud" while they perform on a simple task, like addition. Thinking aloud means simply verbalizing the stream of consciousness, and not explaining or justifying actions to the interviewer. The interviewer does not ask questions, but merely prompts the learner to "say what you are thinking" whenever the learner stops talking. Then the learner is given the target problem-solving task, and recorded on audio tape. The resulting "protocol" can then be analyzed for evidence of the prior knowledge and differences in thinking processes (Robertson, 1990).

The situated learning community is developing techniques for using video recordings to study prior knowledge in full social and environmental context (Roschelle & Goldman, 1991; Suchman & Trigg, 1991; Jordan, in preparation). Typically, a small group of learners is recorded on video tape as they work on and discuss a common task. The camera is set to a constant, wide-angle shot and left unattended, so as to avoid intrusion. Care is taken to get good audio. When the video is finished it may be put to several uses. Learners may review the video with an interviewer, creating an opportunity to interpret their own behavior. In addition, it is often helpful to watch the video with a multidisciplinary panel of colleagues; surprisingly diverse interpretations will often emerge. Finally, the strongest benefit of video is that when a problematic event occurs, the investigator can review it repeatedly. With repeated viewing and conscious cultivation of multiple perspectives, an investigator will begin to sense each participant's prior knowledge and dispositions.

Conclusions: Prior Knowledge and Museum Assessment

Prior knowledge has diverse and pervasive effects on the learning. Museum experiences cannot eliminate or disable prior knowledge, but rather must work with it. Thus museums, like all educational institutions, must come to grips with the paradox of continuity: prior knowledge is both necessary and problematic. Conceptual change must somehow resolve, overcome or avoid this paradox.

Prior knowledge is implicated in both failure and success; thus knowledge is best seen as raw material to be refined. Instead of assuming bipolar dichotomies where desired knowledge replaces prior knowledge, designers should expect learning to occur through a transformative, restructuring process that produces integrative wholes that coordinate pre-existing parts. Refinement and restructuring occurs incrementally and gradually; conceptual change is hard work and takes a long time.

Museums are potentially well-positioned as sites for conceptual change. Museums provide the visitor with opportunities to experience authentic objects directly. Cognitive confrontations provoked by interaction with objects are at the heart of Piaget's theory, as well as Dewey's. Musuems allow visitors to learn socially in small, voluntary groups. Social discourse is the major means of conceptual change in Vygotsky's theory, as well as the contemporary views of situated learning. Museums can provide novel and challenge settings with opportunities for interaction, contemplation, and inquiry. Dewey focuses attention on the problematic nature of learning experiences, and the need for educators to anticipate the resources that learners will need to resolve the conceptual struggles that arise. Museums can provide intellectual, physical, and social resources to aid in the resolution of problematic experience.

But too often in my experience, museums do not rise to this challenge; rather than acknowledging and working from the learner's point of view, museums present an aggressively professional point of view. Too often exhibit seem to assume that a good presentation will make underlying concepts obvious, and therefore provide little or no resources when I find the exhibit problematic: alien, awkward, confusing, frustrating, inaccessible, incomprehensible, mysterious, offensive, opaque, strange, or just too exotic. Too often museums neglect the social nature of visits, and I find interaction difficult or uncomfortable.

Success, however, need not be hard to come by. Success begins with cultivation of the ability to look, listen, and understand the learner's viewpoint, and to discover the seeds from which knowledge and identity can grow. Other institutions, especially schools, do a downright awful job of support conceptual change, as is well-documented throughout the literature. People are naturally active, life-long learners. As Csikszentmihalyi points out, museums need not do much more than provide a high quality experience that engages prior knowledge in an achievable intellectual challenge, and help visitors assemble the physical, intellectual and social resources they will need to succeed. Unlike schools, museums don't have to *make* visitors learn on a particular schedule; museums can focus on catalyzing a spontaneous reaction involving prior knowledge, authentic objects, social interaction, and resources for inquiry.

Assessing long-term success is a more difficult matter. As became clear in during the conference, museums have goals beyond subject matter content: encouraging curiosity, caring and exploration; providing a positive, memorable experience; supporting constructivist learning processes; and developing a sense of personal, cultural and community identity. An excessive focus on *knowledge* can work to the detriment of these other goals, and miss the importance of museum learning entirely. Throughout this chapter, I have argued that dramatic conceptual change is a slow, unpredictable, difficult process. It is thus inappropriate to expect deep conceptual change to predictably occur in a single or short series of visits. Conversely, when deep conceptual change does occur, it will almost certainly involve resources beyond the museums control such as books, videos, science kits, classes, clubs, etc. Assigning partial credit for long-term learning accomplishments is a dubious business at best. Finally, narrowing the museum's focus to changes in conceptual content may harm other, equally worthy goals. For example, curiosity and exploration may fall by the wayside in an attempt to focus on subject matter, and personal and cultural identity may become defined primarily in relation to the community that owns the subject matter, rather than opening to diverse modes of participation.

Prior knowledge nonetheless is implicated in all the museums goals. Curiosity, caring, and exploration begin with what you know now. A memorable experience reaches unites prior knowledge, present experience, and future purposes in a coherent way. Constructivist learning requires attention to the continuity of knowledge. Knowledge and identity are bound together— we choose personal futures based on what we know and understand today. Thus in assessing museum learning, we can neither overemphasize nor ignore prior knowledge.

This suggests that long-term museum assessment should focus on *how museums activate visitor's prior knowledge,* opening new and effective roads for long-term learning. Do museums raise visitors awareness of alternative perspectives? Do visitors formulate personally relevant questions? Do visitors realize how they can tap their current knowledge to enter a new field of inquiry? Do museums provide models of constructive learning processes with which visitors can go on learning? Do visitors become aware of books, videos, and other resources that start from what they know already? Are museums a place where visitors can use prior knowledge to help their friends and family learn? Do museums provide a setting for integrating diverse that make a rich understanding?

The many powerful and poignant stories related at the conference suggest that museums do activate prior knowledge in these and other remarkably powerful ways. While assessment won't prove that museums *cause* long-term conceptual change, a variety of methods could bring to light the diverse ways in which museums can start with access points close to what a visitor knows already and can open the gate to those modes of inquiry, participation, and experience which our society values most highly.

References

Anzai, Y. & Yokohama, T. (1984). Internal models in physics problem solving. *Cognition and Instruction, 1,* 397-450.

Berieter, C. (1985). Towards a solution of the learning paradox. *Review of Educational Research, 13,* 233-341.

Black, M. (1962). Models and metaphors. Ithaca, NY: Cornell University Press.

Boyd, R. (1986). Metaphor and theory change: What is "metaphor" a metaphor for? In A. Ortony (Ed.), *Metaphor and thought.* Cambridge: Cambridge University Press.

Brown, A.L.. & Ferrara, R.A. (1985). Diagnosing zones of proximal development. In J.V.Wertsch (Ed.), *Culture, communication, and cognition.* Cambridge: Cambridge University Press.

Brown, J.S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher,* **18**, 32-42.

Carey, S. *Conceptual change in childhood.* Cambridge, MA: MIT Press.

Champagne, A.B., Gunstone, R.F., & Klopfer, L.E. (1985). Consequneces of knowledge about physical phenomena. In L.H.T. West and A.L. Pines (Eds.), *Cognitive Structure and Conceptual Change.* New York: Academic Press.

Chi, M.T.H., Feltovich, P.J., & Glaser, R. (1980). Categorization and representation of physics problems by novices and experts. *Cognitive Science, 5*, 121-152.

Clement, J., Brown, D.E., & Zietsman, A. (1989). *Not all preconceptions are misconceptions: Finding "anchoring conceptions" for grounding instruction on students' intuitions.* Paper presented at the annual meeting of the American Educational Research Association, San Francisco, CA.

Cohen, R., Eylon, B., & Ganeil, U. (1983). Potential differences and current in simple electric circuits: A study of students' concepts. *American Journal of Physics, 51,* 407-412.

Collins, A., Brown, J.S, & Newman, S. (1989). Cognitive apprenticeship: Teaching the craft of reading, writing, and mathematics. In L.B. Resnick (Ed.), *Knowing, learning, and instruction: Essays in honor of Robert Glaser.*Hillsdale, NJ: Lawrence Erlbaum.

Confrey, J. (1990). A review of the research on student conceptions in mathematics, science, and programming. *Review of Research in Education.*

Corsini, R.J. (1994), Encyclopedia of Psychology, 2nd Edition, New York: John Wiley, p 86-89.

Dewey, J. (1938a). *The logic of inquiry.* New York: Henry Holt.

Dewey, J. (1938b). *Experience and education.* New York: Macmillan Company.

Dewey, J. (1916). Democracy and education. New York: Macmillan Company.

diSessa, A.A. (1993). Towards an epistemology of physics. *Cognition and Instruction, 10(2 & 3),* 105-225.

diSessa, A.A. (1983). Phenomenology and the evolution of intuition. In D. Gentner & A.L. Stevens (Eds.), *Mental models.* Hillsdale, NJ: Earlbaum.

diSessa, A.A. (1982). Unlearning Aristotelean physics: A study of knowledge-based learning. *Cognitive Science*, *6*, 37-75.

Edwards, P. (1967). The encyclopedia of philosophy. New York: Macmillan.

Einstein, A. (1961). Relativity: The special and general theory. New York: Crown Publishers.

Einstein, A. (1950). *Out of my later years.* New York: Philosophical Library.

Ericsson, K.A. & Simon, H.A. (1984). *Protocol Analysis.* Cambridge, MA: MIT Press.

Eylon, B. & Linn, M.C. (1988). Learning and instruction: An examination of four research perspectives in science education. *Review of Educational Research, 58(3)*, 251-301.

Gentner, D. & Gentner, D.R., (1983). Flowing waters or teeming crowds: Mental models of electricity. In D. Gentner & A.L. Stevens (Eds.), *Mental models.* Hillsdale, NJ: Earlbaum.

Ginsburg, H. & Opper, S. (1979). Piaget's theory of intellectual development. Englewood Cliffs, N.J: Prentice-Hall.

Glaserfeld, E.V. (1984). An introduction to radical constructivism. In P. Watlawick (Ed.), *The invented reality.* New York: W.W. Norton.

Gruber, H.E. & Voneche, J.J. (Eds.) (1977). The essential Piaget. New York: Basic Books.

Halhoun, I.A., & Hestenes, D. (1985a). The initial knowledge state of college physics students. *American Journal of Physics*, *53*, 1043-1055.

Halhoun, I.A., & Hestenes, D. (1985b). Common sense concepts about motion. *American Journal of Physics*, *53*, 1056-1065.

Hammer, D.M. (1991). *Defying commonsense: Epistemological beliefs in an introductory physics course.* Unpublished doctoral dissertation, University of California, Berkeley.

Harel, I. & Papert, S. (Eds.) (1991). Constructionism. Norwood, NJ: Ablex.

Hickman, M. (1985). The implications of discourse skills in Vygotsky's developmental theory. Brown, A.L.. & Ferrara, R.A. (1985). Diagnosing zones of proximal development. In J.V.Wertsch (Ed.), *Culture, communication, and cognition.* Cambridge: Cambridge University Press.

Inhelder, B. & Piaget, J. (1958). The growth of logical thinking from childhood to adolescence: An essay on the construction of formal operational structures. London: Routledge.

Jordan, B. (In preparation). *Interaction analysis: Foundations and theory.*

Keil, F.C. (1979). *Semantic and conceptual development. An ontological perspective.* Cambridge, MA: Harvard University Press.

Knorr, Karin. (1981). *The manufacture of knowledge: An essay on teh constructivistand contextual nature of science.* Oxford: Pergammon Press.

Koedinger, K.R. & Anderson, J.R. (1990). Abstract planning and perceptual chunks: Elements of expertise in geometry. *Cognitive Science, 114(4)*, 511-550.

Kuhn, D., Amsel, E., & O'Loughlin, M. (1988). The development of scientific thinking skills. San Diego, CA: Academic Press.

Kuhn, T. (1970). The structure of scientific revolutions. Chicago: University of Chicago.

Latour, B. (1987). Science in action. Cambridge, MA: Harvard Univerisity Press.

Larkin, J.H. (1983). The role of problem representation in physics. In D. Gentner & A.L. Stevens (Eds.), *Mental models.* Hillsdale, NJ: Earlbaum.

Larkin, J.H., McDermott, J., Simon, D.P., & Simon, H. (1980). Expert and novice performance in solving physics problems. *Science, 208*, 1335-1342.

Lave, J. (1988). Cognition in Practice. Cambridge, UK: Cambridge University Press.

Lave, J. & Wenger, E. (1989). *Situated learning: Legitimate peripheral participation.* Cambridge, UK: Cambridge University Press.

Lewis, E.L. (1991). *The process of scientific knowledge acquisition of middle school students learning* *thermodynamics.* Unpublished doctoral dissertation. University of California, Berkeley..

Lightman, A.P. (1989). Magic on the mind: Physicists' use of metaphor. *The American Scholar,* Winter issue, 97-101.

McCloskey, M. (1983). Naive theories of motion. In D. Gentner & A.L. Stevens (Eds.), *Mental models.* Hillsdale, NJ: Earlbaum.

McDermott, J.J. (1981). *The philosophy of John Dewey.* Chicago: University of Chicago Press.

McDermott, L.C. (1984). Research on conceptual understanding in mechanics. *Physics Today, 37*, 24-32.

Minstrell, J. (1989). Teaching science for understanding. In L.B. Resnick & L. Klopfer (Eds.) *Towards the thinking curriculum* (133-149). Alexandria, VA: Association of Supervision and Curriculum Development.

Moschkovich, J.N. (1992). Making sense of linear equations and graphs : an analysis of students'conceptions and language use. Unpublished doctoral dissertation. University of California, Berkeley.

Newell, A. & Simon, H.A. (1972). Human problem solving. Englewood Cliffs, NJ: Prentice-Hall.

Newman, D., Griffith, P., & Cole, M. (1989). The construction zone: working for cognitive change in school. Cambridge, UK: Cambridge University Press.

Miller, A.I. (1986). *Imagery and scientific thought.* Cambridge, MA: MIT Press.

Nercessian, N.J. (1988). Reasoning from imagery and analogy in scientific concept formation. *PSA, 1*, 41-47.

Palinscar, A.S. & Brown, A.L. (1984). Reciprocal teaching of comprehension-fostering and monitoring activities. *Cognition and Instruction*, Hillsdale, NJ: Lawrence Earlbaum.

Piaget. J. (1970). The child's conception of movement and speed. New York: Basic Books.

Posner, G.J. & Gertzog, W.A. (1982). The clinical interview and the measurement of conceptual change, *Science Education, 66,* 195-209.

Posner, G.J, Strike, K.A., Hewson, P.W., & Gertzog, W.A. (1982). Accomodation of a scientific conception: Towards a theory of conceptual change. *Science Education, 66(2),* 211-227.

Posner, M.I. (Ed.) (1989). *Foundations of cognitive science.* Cambridge, MA: MIT Press.

Resnick, L.B. (1983). Mathematics and science learning: A new conception. *Science, 220*, 477-478.

Resnick, M. (1992). Beyond the centralized mindset: Explorations in massively parallel microworlds. Unpublished doctoral dissertation. Massachusetts Institute of Technology.

Robertson, W.C. (1990). Detection of cognitive structure with protocol data: Predicting performance on physics transfer problems. *Cognitive Science, 14*, 253-280.

Rogoff, B. (1990). *Apprenticeship in thinking: Cognitive development in social context.* Oxford: Oxford University Press.

Roschelle, J. (May 1994). Collaborative Inquiry: Reflections on Dewey and Learning Technology. *The Computing Teacher.* 3-9.

Roschelle, J. (1991). *Students' construction of qualitative physics knowledge: Learning about velocity and acceleration in a computer microworld.* Unpublished doctoral dissertation, University of California, Berkeley.

Roschelle, J. and Clancey, W.J. (1992). Learning as social and neural. *Educational Psychologist, 27,* 435-453.

Roschelle, J. & Goldman, S. (1991). VideoNoter: A productivity tool for video data analysis. *Behavior*

Research Methods, Instruments, and Computers, 23, 219-224.

Schön, D. (1979). Generative metaphor. A perspective on problem-setting in social policy. In A. Ortony (Ed.), *Metaphor and thought.* Cambridge: Cambridge University Press.

Scott, P.H., Asoko, H.M., Driver, R.H. (1991). Teaching for conceptual change: A review of strategies. In R. Duit, F. Goldberg, & H. Niedderer, Research in Physics Learning: Theoretical issues and empirical studies. Kiel, Germany: IPN.

Simon, H.A. & Kaplan, C.A. (1989). Foundations of Cognitive Science. In M.I. Posner (Ed.), *Foundations of Cognitive Science.* Cambridge, MA: MIT Press.

Smith, J.P., diSessa, A.A., Roschelle, J. (1993). Misconceptions reconceived: A constructivist analysis of knowledge in transition. *Journal of the Learning Sciences, 3(2),* 115-163.

Songer, N.B. (1989). *Promoting integration of instructed and natural world knowledge in themodynamics.* Unpublished Doctoral Dissertation. University of California, Berkeley.

Spohrer, J.C., Soloway, E., & Pope, E. (1989). A goal/plan analysis of buggy Pascal programs. In E. Soloway & J.C. Spohrer (Eds.) Studying the novice programmer (pp. 355-399). Hillsdale, NJ: Lawrence Erlbaum Associates.

Strike, K.A. & Posner, G.J. (1985). A conceptual change view of learning and understanding. In L.H.T. West and A.L. Pines (Eds.), *Cognitive Structure and Conceptual Change.* New York: Academic Press.

Suchman, L. & Trigg, R. (1991). Understanding practice: Video as a medium for reflection and design. In J. Greenbaum & M Kyng (Eds.), *Designing by doing: A tool box approach to collaborative system design.* Hillsdale, NJ: Earlbaum.

Toulman, S. (1972). Human Understanding. Princeton, NJ: Princeton University Press

Trowbridge, D.E. & McDermott, L.C. (1980). Investigation of student understanding of acceleration in one dimension. *American Journal of Physics, 50*, 242-253.

Tversky, A., & Kahneman, D. (1982). Judgement under uncertainty: Heuristics and biases. In D. Kahneman, P. Slovic, & A. Tversky (Eds.) *Judgement under uncertainty: Heuristics and biases.* Cambridge: Cambridge University Press.

VanLehn, K. (1989). *Mind bugs: The origins of procedural misconceptions.* Cambridge, MA: MIT Press.

Vygotsky, L. (1986). *Thought and Language.* Cambridge, MA: MIT Press.

Wertheimer, M. (1982). *Productive Thinking.* Chicago: Unversity of Chicago Press.

Wertsch, J.T. (1985). *Vygotsky and the social formation of mind.* Cambridge, MA: Harvard.

West,L.H.T. & Pines, A.L. (Eds.) (1985). *Cognitive Structure and Conceptual Change.* New York: Academic Press.

White, B.Y. (1993). ThinkerTools: Causal models, conceptual change, and science education. *Cognition and Instruction, 10(1),* 1-100.

White, R.T. (1985). Interview protocols and dimensions of cognitive structure. In L.H.T. West and A.L. Pines (Eds.), *Cognitive Structure and Conceptual Change.* New York: Academic Press.

Wiser, M. & Carey, S. (1983). When heat and temperature were one. In D. Gentner & A.L. Stevens (Eds.), *Mental models.* Hillsdale, NJ: Earlbaum.