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Mathematics and Science Learning: A New Conception

Lauren B. Resnick

Summary. Findings in cognitive science suggest new approaches to teaching in science and mathematics.

In the last few years a new consensus on the nature of learning has begun to emerge, stimulated by research in the field that has come to be known as cognitive science. The emerging conception of learning has a direct bearing on how science and mathematics can be taught most effectively.

I will sketch here a few examples of recent findings in cognitive science, many of which support the intuition of our most thoughtful teachers. In physics and other sciences, according to these studies, even students who do well on textbook problems often cannot apply the laws and formulas they have been drilled on to interpreting actual physical events. This observation has been made on all kinds of students, including gifted middle-school children and students at some of our most prestigious universities (*1, 2*). The inability to apply routines learned in school is consistent with recent findings from the National Assessment of Educational Progress showing that mathematical problem-solving skills of American children lag far behind their calculation abilities (*3*).

Another well-supported finding is that all students, the weak as well as the strong learners, come to their first science classes with surprisingly extensive theories about how the natural world works. They use these "naïve" theories to explain real world events before they have had any science instruction. Then, even after instruction in new concepts and scientifically supported theories, they still resort to their prior theories to solve any problems that vary from their textbook examples (*4–6*). Some studies have shown that students' prior theories can actually interfere with learning scientific concepts. The students' naïve theories affect what they perceive to be happening in classroom demonstrations or laboratory experiments, and they continue to attach their naïve meanings to technical terms (for example, the term acceleration).

Several studies show that successful problem-solving requires a substantial amount of qualitative reasoning (*7–9*). Good problem-solvers do not rush in to apply a formula or an equation. Instead, they try to understand the problem situation; they consider alternative representations and relations among the variables. Only when they are satisfied that they understand the situation and all the variables in it in a qualitative way do they start to apply the quantification that we often mistakenly identify as the essence of "real" science or mathematics.

These demonstrations of the potent role of naïve theories in science learning, and of the central role of qualitative understanding of a situation in problem-solving, contribute to a new conception of the learner and the learning process that is emerging from cognitive research in mathematics and science. This research has in just a few years produced a new consensus on the nature of learning that is not yet widely reflected in the way mathematics and science teaching is conducted in the schools.

There are many complexities, but the fundamental view of the learner that is emerging can be expressed quite simply.

First, learners construct understanding. They do not simply mirror what they are told or what they read (*10, 11*). Learners look for meaning and will try to find regularity and order in the events of the world, even in the absence of complete information. This means that naïve theories will always be constructed as part of the learning process.

Second, to understand something is to know relationships. Human knowledge

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is stored in clusters and organized into schemata that people use both to interpret familiar situations and to reason about new ones. Bits of information isolated from these structures are forgotten or become inaccessible to memory.

Third, all learning depends on prior knowledge. Learners try to link new information to what they already know in order to interpret the new material in terms of established schemata. This is why students interpret science demonstrations in terms of their naïve theories and why they hold onto their naïve theories for so long. The scientific theories that children are being taught in school often cannot compete as reference points for new learning because they are presented quickly and abstractly and so remain unorganized and unconnected to past experience.

What does this new understanding of the learner suggest about how we can improve mathematics and science education? First, it is never too soon to start. From their earliest years, children are developing theories about how the world works. There is reason to believe that naïve theories will not take hold so firmly if scientific theories become available to them early. Furthermore, it is becoming clear that it takes a long time, and many different examples, for understanding to develop. It is not reasonable to postpone the beginning of this process to a high school or college course.

Second, teaching has to focus on the qualitative aspects of scientific and mathematical problem situations. Too quick an advance to formulas and procedures will not help children acquire the kinds of analytical and representational skills they need. Extensive qualitative analysis is not common in science or mathematics teaching. It may seem to take too much classroom time, and many teachers are perhaps too inexperienced in these ways of thinking. But the new evidence about learning makes it clear that we cannot avoid taking on this task.

A focus on qualitative analysis and understanding of situations does not mean a retreat from the teaching of computational procedures or scientific formulas, or from the basic factual information in any discipline. There is definitely an important role for the traditional skills of mathematics and science and the facts that underlie them. But the procedures and formulas must be treated as matters that make sense, and children must be involved in the task of making sense of them. Research has not yet told us whether it is better to first become skillful at a procedure and then analyze it, or to allow procedures to grow out of understanding a situation. But research has made it clear that procedures must take on meaning and make sense or they are unlikely to be used in any situation that is at all different from the exact ones in which they were taught.

Finally, since naïve theories are inevitable, teachers will probably have to confront them directly. Students may have to be forced to pit their theories against the ones they are being asked to learn, to deal with conflict between theories in much the way that scientists do. This, too, is a new challenge, for only rarely today does teaching explicitly acknowledge children's prior theories (except to mark them wrong) or even recognize the difficult intellectual work entailed in giving them up or substantially revising them.

Research in cognitive science is not only changing our views of how people learn science and mathematics but is also shaping a theory of learning in which the content of what is learned plays a central role. In the past, it has often been difficult for mathematicians and scientists to find in the work done by psychologists and other behavioral scientists much that seemed directly relevant to the problems of teaching their disciplines. The general principles that psychologists produced seemed too far removed from the specific questions of curriculum content that concerned the scientists and mathematicians. That has changed.

A critical theme of the past several years of work in cognitive science has been that a person's intelligent performance is not a matter of disembodied "processes of thinking" but depends intimately on the kind of knowledge that the person has about the particular situation in question. This has led cognitive scientists to recognize that in order to understand complex learning they must study how people learn particular subject matters. As a result, there are now cognitive scientists actively engaged in studying mathematics learning in particular, physics learning in particular, and so forth. At the same time, mathematicians and physical and biological scientists have begun to study the cognitive processes involved in learning their disciplines, often in direct collaboration with psychologists.

This kind of collaboration has been significantly invigorated by grant programs of the National Institute of Education and the now disbanded Science Education Directorate of the National Science Foundation, but these collaborative links are still fragile. In times of retrenchment it is easy to return to traditional alliances and the familiarity of one's own discipline. To keep the collaboration alive, we must give careful attention to supporting vigorous programs of cognitive research in mathematics and science learning. If this is done, the educational payoffs are likely to be large and not unduly long in coming.

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