Science for All Children

A Guide to Improving Elementary Science Education in Your School District

NATIONAL SCIENCE RESOURCES CENTER
NATIONAL ACADEMY OF SCIENCES • SMITHSONIAN INSTITUTION

NATIONAL ACADEMY PRESS
Washington, D.C. 1997

2

How Children Learn

But there is a strong hunch that the early learning, or lack of it, is crucial; and where the early learning has been missed there is an equally strong hunch that what was missed early cannot be faked or by-passed.
— David Hawkins, *Daedalus*, 1983

For more than 50 years, cognitive scientists have been observing how children approach and solve problems. Their work has resulted in an impressive body of research about the learning process. Building on and modifying the foundation laid by Jean Piaget in the 1920s through the 1960s,[1] cognitive scientists have been able to draw some general conclusions about what is needed for effective learning to take place.

Cognitive science is a complex field. It is not our intention to explore all aspects of the field or to give a complete history of it. Our goal is to show how the findings of cognitive scientists support inquiry-centered science education at the elementary level. We will focus on two principles that have grown out of cognitive science and have important implications for effective science teaching and learning.

1. As part of the learning process, children develop theories about the world and how it works. We now know that children construct understanding and develop theories about the world on the basis of their experience. Lauren Resnick describes the process as follows: "Learners try to link new information to what they already know in order to interpret the new material in terms of established schemata."[2] The implication of this for educators is that it is important to begin building children's experiential base in the primary grades by providing research-based, inquiry-centered experiences.

2. The development of the human brain follows a predictable path. The developing biological structures in the brain determine the complexity of thinking possible at a given age. Educators must be aware of stages of growth and be prepared to teach what is developmentally appropriate for children in each grade throughout elementary school.

Incorporating these two basic concepts of cognitive science into an elementary science program can lead to the development of more effective learning experiences. In the following sections, we will explore some of the implications of these concepts.

The Role of Inquiry-Centered Experiences in Elementary Science

Educators have long debated the relationship between hands-on learning and book learning in the classroom. In the 1960s, some disciples of cognitive psychologist Jean Piaget were advocates of pure "discovery" learning; taken to the extreme, an advocate of this school of thought might suggest that the most effective way for children to learn about buoyancy would be to give them a basin of water and a variety of floating and sinking objects and have them learn what they can from these materials. Left to their own devices, some children may discover that some of the objects float while others sink. The teacher would then be requested to help the children make sense of their findings.

Because experience has shown that most children need some guidance in order to learn, by the 1970s, many educators believed that a more realistic way to organize the classroom is through a combination of instruction and hands-on experiences.[3] These educators acknowledged that hands-on experiences generate excitement and enthusiasm for children and provide them with valuable learning experiences. At the same time, the educators had come to see that it is impossible to learn everything this way; some things, such as the names of the planets and their position in the solar system or the concept of life cycles, need to be introduced by the teacher. The challenge for teachers becomes deciding how to integrate didactic instruction and inquiry-centered experiences.

In the past, many teachers have tended to rely on books and pictures to teach science concepts. When possible, some have used hands-on experiences to reinforce that learning. The problem with this approach is that students may have no real-life experiences that relate to this information. Children learn best when they can link new information to something they already know. Therefore, it is often most effective to introduce a new concept by providing children with inquiry-centered experiences. By doing so, educators provide students with a firmer foundation on which to attach the information they will receive later on from other sources. Lawrence Lowery summarizes these ideas: "Books are important. We can learn from them. But books can only do this if our experiential foundation is well prepared. To learn geometry, we must have experience handling geometric forms and comparing them for similarities and differences. To learn about electricity, we must explore relationships among batteries, wires, and bulbs."[4]

Furthermore, inquiry-centered experiences generate one of the most essential ingredients of learning—curiosity. Jane Healy writes, "As well-intentioned parents and teachers, we all sometimes end up taking charge of learning by trying to 'stuff' [the child] rather than arranging things so that the youngster's curiosity impels the process. Children need stimulation and intellectual challenges, but they must be actively involved in their learning, not responding passively."[5]

Lowery believes that curiosity serves an even larger function. He describes it as a "trigger" that helps build crucial connections in the brain. These connections enable children to synthesize specific pieces of information, such as observations of color, form, and texture of an object, into the larger concept of one object with all these attributes. According to Lowery, the ability to synthesize is the essence of intelligence, and intelligence is the product of the quality and quantity of connections in the brain. He believes that educators would do well to capitalize on curiosity in the classroom because it sparks the formation of these connections.

The Implications of Cognitive Research

Children have a strong, innate desire to make sense of the world—and for good reason. With an array of sensory information flooding into the brain, coupled with growing motor skills and cognitive abilities, it is imperative for even the very young child to organize the data.

The way children begin to structure information in their minds depends on a variety of factors, including their individual experiences, their temperament and personality, and their culture. As these factors come together, children develop unique and enduring theories about the world and how it works. For example, a preschooler may observe that many living things, such as people, dogs, cats, and birds, have the ability to move on their own. On this basis, he or she may assume that one characteristic of living things is the ability to move on their own. This notion, while partially correct, discounts plants—a whole other world of living things. Yet to young children, this theory is satisfying, because it organizes a portion of their experience in a way that makes some sense.

Researchers have explained this "theory-making" ability in children in different ways. Howard Gardner has called such ideas part of the "unschooled mind."[6] Resnick uses the term "naive theories" and maintains that children use such theories to explain real-world events before they have had any formal instruction.[7] Gardner and Resnick agree that even after starting school, children continue to hold on tightly to their early ideas and theories.

For example, consider Deb O'Brien's fourth-grade class in Massachusetts.[8] In developing a unit on heat for her class, O'Brien began by asking students for their ideas about heat. To her surprise, she discovered that after nine long winters during which they had been told repeatedly to put on their sweaters when they got cold, the students were convinced that the sweaters themselves produced heat. This was their "naive theory." O'Brien decided to give the students a chance to find out for themselves whether sweaters actually generate heat. She challenged her students to design an experiment to demonstrate "sweater heat." The students put thermometers in their sweaters to measure their temperature. Their hypothesis was that the temperature would rise, indicating that the sweaters were indeed "warm."

O'Brien assumed that after observing a stable sweater temperature, the students would realize their misunderstanding, and the class would move on. But she was mistaken. Although the temperature of the sweaters stayed consistently at 68 degrees Fahrenheit, the students did not accept this evidence immediately. One student, Katie, wrote in her journal: "Hot and cold are sometimes strange. Maybe [the thermometer] didn't work because it was used to room temperature."

The students held to their beliefs through several trials. It was only after they had done everything they could think of—from keeping the thermometers in the sweaters for long periods of time, to moving the sweaters to another location, to wrapping the sweaters in sleeping bags—that some children were willing to consider other ideas about heat. In fact, Katie was one of the first to recognize that heat does not come from her sweater but from the sun and her own body.

This example is important because it illustrates how tightly children hold on to their theories and how difficult it is for them to relinquish them, even in the face of conflicting evidence. Nonetheless, O'Brien was able to help some children replace one set of ideas with more accurate information. She did so by following a clearly defined process. First, she allowed time for the children to express their naive theories by discussing what they thought about heat at the beginning of the unit. Second, she used that information to design the major part of the unit—having the students devise experiments to test their theories. Third, she let the students use their own firsthand experiences as a starting point for reconsidering their old ideas and constructing new knowledge. Fourth, over the long term, she encouraged the students to apply that information to new situations. For example, next winter, when the children put on their sweaters, they will know that the heat they feel comes not from the sweaters but from their own bodies.

Many educators and cognitive scientists believe that this four-step process is at the heart of learning. The process is based on a theory of learning called *constructivism.* Constructivism promotes an important goal of science education—in-depth understanding of a subject, often called *conceptual understanding.* As Susan Sprague explains, "The constructivist model of learning contends that each student must build his or her understanding. In such a process, understanding can never be completed. Each student must work through his or her path toward deeper and deeper understanding and skills."[9]

The process used by O'Brien has been refined and developed into a *learning cycle* that can be incorporated into the science curriculum. The learning cycle typically includes four phases.

1. Focus: Students describe and clarify their ideas about a topic. This is often done through a class discussion, where students share what they know about the topic and what they would like to learn more about. For the teacher, this is a good time to develop an understanding of students' current knowledge and possible misconceptions and to consider how to incorporate this information into the planned lessons. This is also a time to spark excitement and curiosity and to encourage children to consider pursuing their own questions.

2. Explore: Students engage in hands-on, in-depth explorations of science phenomena. During this phase, it is important for students to have adequate time to complete their work and to perform repeated trials if necessary. Students often work in small groups during this phase. They also have the opportunity to discuss ideas with their classmates, which is a valuable part of the learning process.

3. Reflect: Students organize their data, share their ideas, and analyze and defend their results. During this phase, students are asked to communicate their ideas, which often helps them consolidate their learning. For teachers, this is a time to guide students as they work to synthesize their thinking and interpret their results.

4. Apply: Students are offered opportunities to use what they have learned in new contexts and in real-life situations.

As teachers begin implementing the learning cycle in their

In phase 2 of the learning cycle, students engage in hands-on, in-depth explorations. Here, second-graders work together to investigate soil.

classrooms, they may notice that their students seem uncomfortable or reluctant to acknowledge that their naive theories were wrong. These reactions are the result of the internal conflict many students feel as they struggle to give up one set of theories for another. For many students, confronting their previous misconceptions and modifying them represents a difficult intellectual challenge.[10] Therefore, it is important that teachers be aware of their students' struggle and be tolerant of this process and the frustration it may produce.

Ensuring That the Curriculum Is Developmentally Appropriate

While the learning cycle provides a framework for a pedagogical approach, educators must still decide what content to include in the science program. To do so, they must understand children's intellectual development. Piaget's work with children resulted in a theory about intellectual growth that is based on the premise that all children pass through the same stages, in approximately the same order, as they develop. Although many researchers have questioned some of Piaget's ideas and postulated that he underestimated children's cognitive abilities, his theories still provide basic guidelines for educators about the kind of information children can understand as they move through elementary school.

The essence of the model described below, developed by Lowery and based on Piaget's work, is that we can maximize learning by presenting science concepts to children in a way that will be meaningful at each developmental level or stage.[11] The model is based on the human need to organize the information received from the senses in logical, coherent systems. For young children, these systems may be as simple as sorting objects by color or shape. The ability to sort and recognize patterns is particularly important, because children must master these skills before they can learn to read.

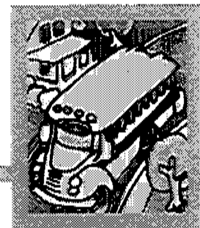
Children learn at different rates, however, and not all children achieve these milestones at the same time. In general, every class in a typical elementary school spans at least a full grade of cognitive developmental levels. The basic stages of cognitive growth, however, may be summarized as follows:

- Through the primary grades, children typically group objects on the basis of one attribute, such as color. When discussing plants, primary school students will be able to sort them by color or size, but they probably cannot perform both steps *at the same time.* In fact, it is a major cognitive leap when children, at about fourth grade, are able to organize objects and ideas on the basis of more than one characteristic at the same time. The significance of this information for educators is that young children are best at learning singular and linear ideas and cannot be expected to deal with more than one variable of a scientific investigation at a time. For example, when observing weather, primary school students can study variables such as temperature, wind, and precipitation separately; it is not appropriate to expect them to understand the relationships among these variables. By the upper elementary grades, however, students will be able to consider such phenomena as how wind influences the perceived temperature (the "wind-chill" factor).

- Toward the end of elementary school, students start to make inferences. To some researchers, this marks the beginning of deductive reasoning. At this stage, students also realize that different plants or different animals can be classified into subordinate categories. For example, they understand that all crocodiles are reptiles but not all reptiles are crocodiles. At this stage of development, students are ready to design controlled experiments and to discover relationships among variables. When investigating the frequency of pendulum swings (number of swings in a minute) during a module on time, for example, sixth-grade students can experiment by changing variables, such as the length of the string or the mass of the pendulum bob, and then determining whether one or both of these variables affect the frequency of the pendulum swings.

- From this point on, students' thinking processes continue to become more and more complex. At the onset of adolescence, students not only can classify objects by multiple attributes, they can also experiment with different organizational strategies. For example, they can decide how they want to organize a collection of plants. They may choose to organize by color, size, shape, height, or leaf shape. They become more adept at manipulating these characteristics, which means that their scientific experiments can become increasingly more sophisticated. By age 16, students can understand highly complex organizational schemes, such as the periodic chart of elements and the structure of DNA.

If these developmental steps are not reflected in science instructional materials, there will be a mismatch between what children are capable of doing and what they are being asked to do. For example, it is inappropriate to expect a nine-year-old to understand the abstract concept of acceleration, yet some fourth-grade science programs include this concept. When this kind of mismatch happens over and over again, children do not learn as much as they could about science. Equally important, they do not enjoy science. For some children, this leads to feelings of failure and the development of negative attitudes toward science. If we can modify the curriculum to accommodate different stages of cognitive growth, we will take a big step toward solving such problems.



Key Points

- Inquiry-centered science provides an experiential base that children can relate to information they are acquiring through other sources. Because an experiential base is crucial for learning, it is appropriate to place hands-on learning first, before other kinds of learning take place.
- Children begin forming theories about the world long before they have accurate factual information, and they hold on tightly to these early ideas and theories. For this reason, educators need to be aware that it can take children a long time and many different encounters with a new concept to achieve conceptual understanding.
- To facilitate conceptual understanding on the part of students, the teacher needs to assume a new role in the classroom. He or she needs to create meaningful learning experiences that enable children to construct their understanding and deepen their knowledge of a subject.
- The way to maximize learning at each stage of growth is to present science concepts that are appropriate to the child's developmental level.
- The learning cycle—Focus, Explore, Reflect, Apply—has been applied in thousands of science classrooms. It is an effective way to implement the findings of cognitive scientists.

For Further Reading

Brooks, J. G., and M. G. Brooks. 1993. *In Search of Understanding: The Case for Constructivist Classrooms.* Alexandria, Va.: Association for Supervision and Curriculum Development.

Bybee, R. W., and J. D. McInerney, eds. 1995. *Redesigning the Science Curriculum.* Colorado Springs: BSCS.

Carey, S. 1985. *Conceptual Change in Childhood.* Cambridge, Mass.: MIT Press.

Champagne, A. B., and L. E. Hornig. 1987. "Practical Applications of Theories About Learning." In *This Year in School Science 1987: The Report of the National Forum for School Science,* A. B. Champagne and L. E. Hornig, eds. Washington, D.C.: American Association for the Advancement of Science.

Duckworth, E. 1987. *"The Having of Wonderful Ideas" and Other Essays on Teaching and Learning.* New York: Teachers College Press.

Gardner, H. 1991. *The Unschooled Mind.* New York: BasicBooks.

Hawkins, D. 1983. "Nature Closely Observed." *Daedalus, Journal of the American Academy of Arts and Sciences* Spring: 65-89.

Healy, J. M. 1990. *Endangered Minds: Why Our Children Don't Think.* New York: Simon & Schuster.

Langford, P. 1989. *Children's Thinking and Learning in the Elementary School.* Lancaster, Penn.: Technomic Publishing Company.

McGilly, K., ed. 1994. *Classroom Lessons: Integrating Cognitive Theory and Classroom Practice.* Cambridge, Mass.: MIT Press.

National Research Council. 1996. *National Science Education Standards.* Washington, D.C.: National Academy Press.