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“Don’t Tell Me, I’ll Find Out”: Robert Karplus—A Science Education Pioneer

Robert G. Fuller

Abstract: Robert Karplus (1927–90), who began his career as a brilliant theoretical physicist, switched to science education in the early 1960s. He made many substantial contributions to this field in addition to developing a complete K–6 hands-on science curriculum. Karplus provided his curriculum with a sound epistemological foundation, based on the work of Piaget. He developed an effective classroom teaching strategy, the learning cycle. He and his team used a scientific approach to curriculum development. They focused on teacher development. Karplus was committed to science for ALL students. Through science activities he sought to share the joy of discovery. A recent book collects some of his important papers and enables you to examine his work for yourself and see what you discover.

Key Words: Piaget, learning cycle, discovery, SCIS, science curriculum

INTRODUCTION

Robert Karplus (1927–90) made six major contributions to science education. In fact, without his work science education as we know it in the USA today would be completely different. Because of his sudden and untimely death, Professor Karplus never had a chance to reflect upon or to collect his total body of work. As a young faculty member in physics, my career was significantly changed by my interactions with Bob Karplus and, thanks to a faculty development leave granted to me by the University of Nebraska—Lincoln in the spring of 1999, I was able to interview the co-workers of Robert Karplus and collect several of his important papers into a book that was published in 2002 (Fuller, 2002). This book explores the work of Robert Karplus in science education. It is an attempt to support the claim that several of his contributions to science education are as important today as they were when he first made them nearly thirty years ago.

In this paper I will review the career of Robert Karplus, introduce his enduring contributions to sci-

ence education and invite you to use his work to discover something about science education for yourself.

BIOGRAPHY

Robert Karplus attended Harvard University where he obtained bachelors, masters and PhD degrees. He obtained his PhD in chemical physics in 1948 when he was 21 years old. His PhD thesis had included both experimental and theoretical work and his work was directed by E. Bright Wilson, Jr. After completing his PhD he went to the Institute for Advanced Studies at Princeton. When he was there he worked with Norman Kroll in the new field of quantum electrodynamics (QED). Together they published one of the *first* detailed calculations based on QED. Their joint paper, “Fourth order corrections in QED to the magnetic moment of the electron,” was published in the *Physical Review* in 1950 and brought them both immediate recognition within the physics community.

In 1950, he returned to Harvard University where he remained an assistant professor of physics until

Robert Karplus

1954. That year he moved to the University of California, Berkeley (UCB), as an associate professor and he became a full professor of physics at UCB in 1958, at the age of 31. From 1948 to 1962 he published 50 research papers in physics, mostly in QED, but also on the Hall Effect and Van Allen radiation. He was the senior or only author on the first 19 of those papers. He published with 32 different physicists, including two who later won Nobel prizes in physics. More than 90% of his co-authors went on to become fellows of the American Physical Society.

In 1948, Robert Karplus married Elizabeth Frazier. Bob and Betty were the parents of seven children born between 1950 and 1962, three daughters and four sons. He made his first visits to his daughter's elementary school class in 1959–60. He probably did electrostatics demonstrations with a Wimshurst machine that he had inherited from his grandfather. Those visits piqued his interest and his career made a fairly rapid change from theoretical physics to science education. He joined an elementary school science project with other UCB faculty. He and Herb Thier started the Science Curriculum Improvement Study (SCIS) at the Lawrence Hall of Science on the UCB

campus in 1961. He published his first education paper with J. M. Atkin in 1962. It was entitled "Discovery or Invention?" (Atkin and Karplus, 1962).

Over the next decade, Dr. Karplus and Herb Thier and their co-workers developed a complete K–6 science curriculum, the SCIS curriculum, which is still in use today. He is shown in his Lawrence Hall office in front of the SCIS logo in Fig. 1.

In the 1970s, he turned part of his attention to student reasoning beyond elementary school, a subject on which he published 10 papers. These papers serve as foundational work for a subfield of physics, physics education research, which is practiced in more than a dozen physics departments in universities in the United States today.

Dr. Karplus became the President of the American Association of Physics Teachers in 1977 and was awarded their highest prize, The Oersted Medal, in 1980 for his exceptional contributions to physics and physics education. His professional career was ended in 1982 when he suffered a cardiac arrest while jogging in Seattle in June of 1982 at the age of 55. He died in 1990.

ENDURING CONTRIBUTIONS

Robert Karplus made many enduring contributions to science education. If you look at the national and state standards for science knowledge that have recently been developed in the United States, you will find ideas based on the work of Robert Karplus. I will highlight six of his important contributions.

- *A sound epistemological foundation.* When he became interested in how children learn science, he started to read the professional literature of education and psychology. He brought a scientific approach to his work. First, he thought, find the correct theory and then use that theory to develop the science materials for the children. It was during this time of his work that he studied the writings of psychologists and educational theorists. He found the concepts of Jean Piaget were the closest to his own understanding of scientific reasoning. He was one of the first professionals to take Piaget's work into account for science curriculum development. He realized, based on the work of Piaget, that children build, or construct, their own internal mental schemes for knowing science as they experience the world. Hence, Karplus reasoned, to be effective, a team of people who are developing a science curriculum for children must be aware of the reasoning patterns used by the children. He developed a series of films on student reasoning that are still available today (Karplus and Peterson, 1976).
- *An effective classroom teaching strategy.* Once Karplus and his co-workers had constructed an educational theory for their work, based on their understanding of Piaget's work, they realized that they needed an instructional strategy that would enable them to put their theory into classroom practice. They developed the learning cycle for classroom use which has three phases, known as *Exploration*, *Invention*, and *Discovery*. This learning cycle moved the learning of science from the study of a textbook to hands-on experiences. The learning cycle is explained in more detail in the Karplus paper appended to this paper (Karplus, 1977). I think it is nearly impossible today to find a science curriculum or set of standards that does not have the words hands-on in it somewhere. Most of them have no idea that Robert Karplus was an important part of the development of that method of teaching and learning science.
- *A scientific approach to curriculum development.* When Karplus and his co-workers began to develop materials for classroom use, they used a scientific process of curriculum development. First they would brainstorm content ideas and approaches that they thought would be appropriate and effective. Then they would develop their materials and take them into the schools for field testing by the development team and with schoolteachers. During these field tests they would make detailed observations of both children and teacher behaviors. These notes would then be brought back to team meetings and revisions in the materials would be made. In a process analogous to the cyclic processes used by scientists, theory–experiment–revision of theory, the Karplus team created science learning materials, develop–field test–revise. Many lessons were created and field-tested, only the very best lessons survived.
- *A focus on teacher development.* Perhaps because of the many hours Karplus spent in school classrooms during the development of the SCIS materials, he realized that school teachers needed to develop additional teaching skills to become effective science teachers. So he emphasized teacher development. He, along with others, created a series of teacher workshops on the theme of science teaching and the development of reasoning. The movies he made on student reasoning patterns became a part of the teacher-development workshops.
- *Science for ALL students.* From the beginning Robert Karplus thought of science as a subject for all students. In his first papers and presentations on elementary school science, he emphasized science for everyone. He would not be surprised by a national science standard that calls for science for all

citizens. Karplus and his team tried SCIS lessons in a diverse selection of schools around the country. He believed that elementary science activities needed to excite all students, not just the ones with positive predispositions towards science.

- *Share the joy of discovery.* Throughout his life Robert Karplus was excited by the process of discovering new ideas. His career as a physicist had been fueled by his exploration of the new ideas of QED. His work in science education was driven by his fascination with the responses of children to nature. He enjoyed the act of discovery and wanted science curricula to make that joy available to others. He wanted children to know of joy of discovery. The title of a film for the SCIS primary grade school materials was *Don't tell me, I'll find out* (SCIS, 1969).

A PERSONAL ANECDOTE

Why would Robert Karplus change his career at the age of 32 from one as a successful, outstanding theoretical physicist to become a science educator? His co-workers offered a variety of explanations, from a kind of malaise with his work in theoretical physics to the fact that he and Betty had seven children.

I want to propose a different scenario. While physicists believe there is no discipline with the beauty and parsimony of physics, there was about Robert Karplus a profound curiosity about the whole world. He found, nearly everywhere, intellectual puzzles that intrigued him. I want to tell you a story that I heard from two different physicist colleagues of Karplus who live more than a thousand miles apart.

It goes like this:

Robert Karplus was going to study how children understand kinematics, a foundational aspect of physics.

He placed the toy truck in front of a child.

He rolled the truck slowly across the desk.

"Did the truck move?" he asked.

"No." replied the child.

(It is difficult to learn the fundamental concepts of motion when an object that goes from one location to another does not move, he thought. Perhaps the child misunderstood. So Karplus moved

the truck back to its starting position. Again, he slowly rolled the toy truck across the desk to a new location.)

"Did the truck move?" he asked again.

"No." the child replied once again.

"Can you explain to me why you say the truck did not move?" Karplus asked.

"It did not move," responded the child triumphantly. "You moved it!"

In that moment, Karplus discovered a new puzzle, the importance of language in shaping human reasoning. He began his journey through the works of Wolf, Vygotsky, and Piaget. He had been captured by a challenge worthy of his brilliant mind. The path from outstanding theoretical physics to elementary science had been commenced. Robert Karplus never looked back.

A CHALLENGE TO DISCOVER

Can you discover what it was about helping children learn science that so intrigued Robert Karplus that it lured him away from a very successful career as a theoretical physicist to become a science educator? He went from a position with high cultural esteem to one held in relatively low intellectual regard. In fact, one colleague was reported to have remarked, "What a waste! He was a very gifted theoretical physicist and he gave that up to work with children and teachers." Was it really a waste?

You owe it to yourself to evaluate the contributions of Robert Karplus to the field of science education. How valuable do you think they were? Do you agree that they are as important today as when he first made them? You can start with a position paper he wrote for the *Journal of Research in Science Teaching* in 1977, reproduced in the Appendix to this paper. Then watch him interview students about how they reason and hear him ask a student to explain how he made an *approximate ratio* in his film on *Formal Reasoning Patterns*. See what you can discover for yourself.

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APPENDIX †

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SCIENCE TEACHING AND THE DEVELOPMENT OF REASONING*

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In your interactions with secondary school students learning science, you have probably become aware of large differences in student ability to understand science concepts, conduct investigations, and/or solve specific problems. Some students are extremely capable, while others demonstrate peculiar and inappropriate reasoning strategies. Sometimes, even after your best efforts, they seem unable to grasp ideas that to you are eminently clear. Often students are able to follow problem solutions but are at a loss when required to transfer those strategies to slightly different problems. You wonder why students are able to respond successfully to examination questions and then, after a month or so, forget almost all of what they learned.

Teachers' understanding of these situations and of student differences can be significantly aided by the developmental theory of Jean Piaget. For several years, Wollman and Lawson have worked with me investigating the relation of this theory to science teaching at the secondary school level. Other researchers with whom we have been in touch and whose work has influenced our thinking include Arnold Arons (University of Washington, Seattle), Kenneth Lovell (Leeds, England), Eric Lunzer (Nottingham, England), John W. Renner (Norman, Oklahoma), Michael Shayer (London), and Antonio Suarez (Zurich, Switzerland).

In addition to researching students' reasoning, it is essential to communicate the important features of Piaget's theory to secondary school teachers so that they might apply it in their classrooms and provide larger field tests of its applicability than our small research group could undertake. This paper focuses on an interpretation of Piaget's theory derived from recent findings applicable to adolescents.

Piaget's Theory and Reasoning Patterns

Piaget has characterized human intellectual development in terms of four stages (Inhelder & Piaget, 1958). The first two, called sensory-motor and preoperational, are usually

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David P. Butts, Editor

KARPLUS

completed when a child is seven or eight years old. Following these are two stages of logical operations, called concrete thought and formal thought, which are relevant to secondary school students.

Piaget has ascribed the process whereby individuals advance from one stage to the next to four contributing factors: maturation, experience with the physical environment, social transmission, and "equilibration." The last item designates an internal mental process in which new experiences are combined with prior expectations and generate new logical operations.

To make the stage concept useful, one has to describe the reasoning of an individual whose development has reached each of the stages. This description has been stated by Piaget in terms of the mental operations the individual uses when facing certain problems. To avoid confusion with other uses of the term "operation" in science, it is useful to employ the phrase "reasoning patterns." Two examples of behavior based on reasoning patterns are (1) serial ordering a set of sticks according to their length and (2) investigating the effect of fertilizer on clover by setting up several test plantings that are treated alike in all respects except in the amount of fertilizer applied to them.

From the research of Piaget and others, certain rules have been formulated for identifying reasoning patterns as belonging to concrete or to formal thought. In general, reasoning that makes use of direct experience, concrete objects, and familiar actions is classified as a concrete reasoning pattern, such as example (1) above. Reasoning that is based on abstractions and that transcends experience is classified as a formal reasoning pattern, such as example (2) above. Here is a more extensive list of clues that are helpful in classifying reasoning patterns (Karplus et al., 1977, Module 2).

When using concrete reasoning patterns, the individual:

- C1 Applies classifications and generalizations based on observable criteria (e.g., consistently distinguishes between acids and bases according to the color of litmus paper; all dogs are animals, but not all animals are dogs).
- C2 Applies conservation logic—a quantity remains the same if nothing is added or taken away, two equal quantities give equal results if they are subjected to equal changes (e.g., when all the water in a beaker is poured into an empty graduated cylinder, the amount originally in the beaker is equal to the amount ultimately in the cylinder).
- C3 Applies serial ordering and establishes a one-to-one correspondence between two observable sets (e.g., small animals have a fast heart beat while large animals have a slow heart beat).

By using these patterns, the individual can reason and solve problems beyond his ability in the preoperational stage. Yet there are many limitations if concrete reasoning patterns are compared to formal ones.

When using formal reasoning patterns, the individual:

- F1 Applies multiple classification, conservation logic, serial ordering, and other reasoning patterns to concepts, abstract properties, axioms, and theories (e.g., distinguishes between oxidation and reduction reactions, uses the energy conservation principle, arranges lower and higher plants in an evolutionary sequence, makes inferences from the theory according to which the earth's crust consists of rigid plates).
- F2 Applies combinatorial reasoning, considering all conceivable combinations (e.g., systematically enumerates the genotypes and phenotypes with respect to characteristics governed by two or more genes).
- F3 States and interprets functional relationships in mathematical form (e.g., the rate of diffusion of a molecule through a semipermeable membrane is inversely proportional to the square root of its molecular weight).
- F4 Recognizes the necessity of an experimental design that controls all variables but the one being investigated (e.g., sets up the clover experiment mentioned above).

DEVELOPMENT OF REASONING

TABLE I
Concrete and Formal Reasoning Patterns

CONCRETE	FORMAL
(a) Needs reference to familiar actions, objects, and observable properties.	Can reason with concepts, relationships, abstract properties, axioms, and theories; uses symbols to express ideas.
(b) Uses reasoning patterns C1 - C3, but not patterns F1 - F5.	Uses reasoning patterns F1 - F5 as well as C1 - C3.
(c) Needs step-by-step instructions in a lengthy procedure.	Can plan a lengthy procedure given certain overall goals and resources.
(d) Is not aware of his own reasoning, inconsistencies among various statements he makes, or contradictions with other known facts.	Is aware and critical of his own reasoning; actively seeks checks on the validity of his conclusions by appealing to other known information.

F5 Reflects upon his own reasoning to look for inconsistencies or contradictions with other known information.

In Table I, the most important differences between concrete and formal reasoning patterns are summarized.

Present Status of the Theory of Formal Thought

While each of the two lists in the previous section has a certain theme, this enumeration of formal reasoning patterns does not communicate the unity originally proposed by Piaget. Piaget conceived of formal reasoning patterns as dealing with logical propositions and having the organizational structure of an algebraic group called the INRC group. Recent workers, however, have not found evidence to support Piaget's proposals in these respects. Neimark (1975) has summarized the present status by concluding that there *is* more advanced intellectual functioning than concrete thought, but that such reasoning is not used as reliably and universally as Piaget's writings imply. Lunzer (in press) has expressed similar views. In fact, Piaget (1972) has adopted a more flexible position in the last few years.

One example of a study that leads to difficulty for the highly unified view of formal thought is an unpublished survey of student reasoning in seven countries carried out in 1974 (Karplus et al., 1975). Several thousand eighth- and ninth-grade students were presented with a task in proportional reasoning and a second task requiring control of variables (reasoning patterns F3 and F4). The results indicated that United States students succeeded more frequently on control of variables, while Austrian students succeeded more frequently on proportional reasoning. For British students, performance on the two tasks was more closely similar than for either of the other two samples mentioned. Using the British results as a guide, one might claim that the two tasks are about equally difficult. The lack of correspondence in Austria and the United States can then not be explained by asserting that eighth-graders in one of these countries are more or less advanced toward formal thought than students in the other. The researchers concluded that there were differential effects of instruction that did not generalize directly from one formal reasoning pattern to another.

KARPLUS

In spite of the fact that the unity of formal reasoning patterns appears to be elusive, some research studies suggest strongly that there is a bond relating them. Consider, for instance, the factor structure of 10 Piagetian tasks reported by Lawson and Nordland (1976) after interviewing 96 seventh-graders in an urban school. They identified two principal components that accounted for 55% of the variance in their data. Four tasks—equilibrium in the balance, separation of variables, conservation of displaced volume (both cylinders and clay)—loaded primarily on the first component. Three other tasks (conservation of number, solid amount, and liquid amount) loaded exclusively on the second component. The last three tasks (conservation of length, area, and weight) loaded on both components. The authors concluded that the first and second components represent formal and concrete thought more comprehensively than these are represented in any single reasoning pattern. Perhaps, then, there is a unity after all!

One shortcoming of the Lawson-Nordland study is its emphasis on conservation tasks. Lawson is now planning a more comprehensive investigation that includes a wider variety of reasoning patterns.

Applications to Science Teaching

The science teacher who is interested in applying Piaget's theory can benefit but must be cautious to avoid the difficulties with the theory that are even more prominent in a classroom than they are in a research study. Teachers need to concentrate on identifying their students' reasoning patterns and should not expect that each student's entire behavior can be classified neatly as reflecting either concrete or formal thought. Most important is the teacher's willingness to accept the conclusion, documented in recent studies, that a large fraction of students will use concrete reasoning patterns extensively (Karplus & Peterson, 1970; Karplus et al., 1975).

By becoming aware of reasoning patterns needed to understand a particular science course, a teacher can both identify the conceptual emphasis and demands of the subject matter and help students develop more advanced reasoning patterns than they use currently.

Here are nine concepts that are usually included in secondary school science courses: density, temperature, cell, gene, environment, chemical bond, periodic system of elements, acid-base, and ideal gas. What reasoning patterns must a student use to understand these? (Karplus et al., 1977, Module 7).

Look first at density. Density must be understood in terms of other concepts—mass and volume—rather than in terms of direct experience. Furthermore, the ratio relationship must be applied to mass and volume. Both of these mental steps make use of formal reasoning patterns, items F1 and F3 in the earlier list. For this reason, density may be called a "formal" concept.

Temperature can be defined in terms of sensations (warm/cold) or thermometer readings. When this is done, temperature may be called a "concrete" concept, because it is based on observable criteria and thus requires concrete reasoning patterns (item C1 in the list) for understanding. Temperature, however, can also be defined as a measure of the average molecular kinetic energy. If this is done, temperature becomes a "formal" concept whose understanding derives from other concepts (molecule, kinetic energy), the kinetic molecular theory, and mathematical relationships (items F1 and F3).

This example illustrates that a concept with several meanings may be either "concrete" or "formal," depending on the meaning used. To identify the reasoning required of the students in a course, the teacher must be clear about the meaning of the concepts that are introduced. Special care must be taken to use a concept always with the meaning that was

DEVELOPMENT OF REASONING

explained to the students, and not to expect that the introduction of temperature or another concept as “concrete” concept can be extended automatically to an application of the concept’s “formal” significance.

All the other concepts listed above can be defined as “formal” concepts. Still, “cell,” “environment,” and “acid-base” can also be given definitions as concepts in terms of familiar actions and examples. A cell can be observed when tissue is examined through a microscope; the environment and environmental factors such as heat, moisture, and light can be observed easily; and acid-base can be distinguished by the use of a chemical indicator, interaction with washing soda, or—in safe cases—by tasting.

The remaining concepts—“gene,” “chemical bond,” “periodic system,” and “ideal gas”—all require formal reasoning patterns for their understanding. They can only be defined in terms of other concepts, abstract properties, theories, and mathematical relationships. There is no way of defining them as “concrete” concepts.

The Formation of Reasoning Patterns by Self-Regulation

Problems that a secondary school science teacher is likely to encounter were mentioned at the beginning of this article. Some of these problems can be ascribed to the fact that many students use concrete reasoning patterns, yet that subject matter often requires formal thought. Unless science courses are to become highly selective and admit only students who use formal reasoning patterns with ease, the formation of formal reasoning patterns should be made an important course objective (at least as important as the covering of a certain body of subject matter!).

Let us, therefore, return to the process of intellectual development. Rather than using Piaget’s term “equilibration” for the essential but hard-to-define fourth contribution, one may employ the term “self-regulation,” which has fewer science connotations and emphasizes the active role played by the individual (Karplus et al., 1977, Module 5).

The key to the formation of new reasoning patterns is an individual’s responding to his or her inadequacy in using the present reasoning patterns to cope with a demand. An analogy in physical actions is your response to driving an unfamiliar car with a brake of different stiffness from that in your car. You first use your accustomed foot pressure, discover that it is unsatisfactory, and then try variations until the car responds smoothly. Your first encounter with an unsuspected power brake can lead to near-disaster!

A child using a concrete reasoning pattern in a pizza parlor may decide that the eight-inch pizza costing \$1.25 is too small and may order a 16-inch size without looking at the price, in expectation that it costs \$2.50, “Because it’s twice as big.” Imagine the dismay when the giant pizza arrives, together with a check for about \$5.00! Here is a surprise that may trigger the search for a more successful reasoning pattern to cope with the pizza size/price problem, a mathematical relationship requiring a formal reasoning pattern.

Others have been gathering evidence (Lawson, Blake, & Nordland, 1975; Lawson & Wollman, 1975; Lawson & Wollman, 1976) that the learning cycle, which was introduced as part of the Science Curriculum Improvement Study (1970-1974) to facilitate concept development at the elementary school level, is also effective with older students and the introduction of formal concepts (Shoemaker, 1967; Sticht, 1971). The learning cycle consists of three instructional phases that combine experience with social transmission and encourage self-regulation (SCIS, 1974). These three phases are *exploration*, *concept introduction*, and *concept application*.

During *exploration*, the students gain experience with the environment—they learn through their own actions and reactions in a new situation. In this phase, they explore new

KARPLUS

materials and new ideas with minimal guidance or expectation of specific accomplishments. The new experience should raise questions or complexities that they cannot resolve with their accustomed patterns of reasoning, as in the pizza example. As a result, mental disequilibrium will occur and the students will be ready for self-regulation.

The second phase, *concept introduction*, provides social transmission—it starts with the definition of a new concept or principle that helps the students apply a new pattern of reasoning to their experiences. In the pizza problem, the relation of area to diameter would be the key idea, but might be first illustrated by means of the area and side of a square rather than a circle. The concept may be introduced by the teacher, a textbook, a film, or another medium. This step, which aids self-regulation, should always follow exploration and relate to the exploration activities.

Concept introduction is especially effective when it involves the formal definition of a concept whose concrete definition is already understood by the students. Since, for instance, a square can easily be subdivided into unit squares, determining the area of a square need only make use of concrete reasoning patterns. This illustration would help lead the students toward conceptualizing and approximating the area of a circle, a step that requires a formal reasoning pattern because a circle cannot be subdivided completely into unit squares by a finite number of steps.

In the last phase of the learning cycle, *concept application*, familiarization takes place as students apply the new concept and/or reasoning pattern to additional situations. In the pizza area example, a valuable application activity might involve the construction of sets of similar rectangles, ellipses, and other figures out of cardboard and investigating the relationship of their diameter to their weight. In this phase, physical experience with materials and social interactions with teacher and peers play a role.

Concept application is necessary to extend the range of applicability of the new concept. This phase provides additional time and experiences for self-regulation. Furthermore, concept application activities aid the students whose conceptual reorganization takes place more slowly than average or who did not adequately relate the teacher's original explanation to their experiences. Individual conferences with these students to identify and resolve their difficulties are especially valuable.

Conclusion

This has been a very simplified introduction to a complicated area of research that holds a great deal of promise for the improvement of secondary science teaching. It is most important that Piaget's ideas can and should be used actively for instructional improvement, and should not be interpreted as implying that education must wait until development has occurred spontaneously. Piaget (1973) has described the interaction of education and development in these words: "Thus education is . . . a necessary formative condition toward natural development itself." Of course, the theory will not solve all educational problems, but it can help in those aspects of concept development and understanding which make science courses especially difficult for many students.

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