

Physics for beginners

During the early school years we should provide a highly diversified program based heavily on concrete experiences. The Science Curriculum Improvement Study is one such program.

Robert Karplus

Take a spring, stretch it an inch or two, and imagine the force exerted by it. You will have no difficulty with this problem, and a layman or child will have no difficulty either, especially if you use the term "pull" instead of "force" in your question. Now take a second similar spring, hook it to the first one, and stretch the combination until each spring is extended to the same distance as the single spring before. When you then ask about the pull, most nonphysicists will state that it is obviously twice what it was before, because there are two springs instead of one. Try to convince them that the force has the same magnitude as before, because each spring is stretched by the same amount! How would you proceed?

A related conceptual problem was revealed to me when an enthusiastic first-grade teacher told me of her experiences while teaching about pushes and pulls from a teaching outline I had prepared. To document the program's effectiveness, she described how two pupils had applied the ideas outside their science class, after a brief altercation. Jimmy had been knocked over in the struggle, and Tom explained proudly that this had happened because he (Tom) had pushed harder on Jimmy than Jimmy had pushed on Tom. Ergo, Jimmy fell.

These and similar experiences convinced me that the Newtonian force concept, which plays such a fundamental role in classical physics and is therefore introduced very early in most general physics courses, actually has serious shortcomings as an explanatory device for beginning learners of physics at any age. This is true even when the kinematic background and mathematical limiting processes involving velocity

and acceleration are avoided by basing force directly on operations with elastic objects. In the first example above, the observer may have responded intuitively to the stored energy in the two-spring system, which is indeed twice that of the one-spring system. In the second example, the children failed to identify consistently the objects exerting or experiencing the forces and appeared rather to respond to the sense of energy transfer.

What, then, is the scientific concept one might use when the idea of force is not directly applicable? My studies in quantum field theory suggested that "interaction" is actually a more general

idea than force, or even energy, useful in nonclassical problems that defy description by forces, and also applicable to thermal, electrical, chemical and biological phenomena. Evidence of interaction may be provided by temperature change, color change, motion, phase change, and by other directly observable effects that can be recognized by a beginner in science as well as by an experienced scholar. The force of interaction (or momentum transfer) is measurable if changes of motion are described quantitatively, and can then be used for analysis and prediction. For temperature and phase changes, the heat input



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or output (energy transfer) is a much more useful measure of interaction strength, and work (energy transfer) is often employed for better understanding of changes in motion.

The real pedagogical advantage of the interaction viewpoint is that a qualitative approach is successful. For you have to recognize that reliable measurement and quantitative descriptions and relationships are not part of the cultural environment in which most people (parents, teachers, students) function. Outside the sciences—and more particularly the physical sciences—appearances, feelings and impressions are much more

powerful than numerical reasoning. I believe that some progress in overcoming this limitation can be made by introducing energy transfer and force after interaction is understood, but I am convinced that the success of the entire science-teaching program must not be allowed to hinge on an early understanding of these quantitative concepts.

These remarks are intended to introduce the view of physical theory taken by the Science Curriculum Improvement Study (SCIS). In the last ten years, the SCIS developed an elementary-school science-teaching program whose objective is the increase of scientific literacy in the school and adult populations. The general strategy of this program is to confront elementary-school children with firsthand experiences of natural phenomena and with intellectual challenges that will stimulate their further cognitive development. This approach means that the elementary-school classroom must, in essence, be converted into a science laboratory where each child can manipulate apparatus, look for answers to his questions and observe the outcome of his own actions. Key ideas that are useful for interpreting the observations are introduced by the teacher or by children. These ideas include *properties* of the objects used, the *interaction* concept, notions of *energy sources* and *receivers*, *variables* to account for differences in the outcomes of successive experiments, and *scientific models* to explain observations. Life-science concepts lead from *organisms* and their interaction

with the *environment* to the *ecosystem*. Many aspects of this program are valuable for teaching beginners of any age.

Why elementary-school science?

Just how important a part science teaching can and should play in the elementary school has not been generally recognized until the last ten years. Previously it was thought that the children's ability of rational thinking was only adequate for a program that emphasized the basic skills of reading, writing and arithmetic. Other areas, such as science and social studies, were taught in a context of activities oriented around the basic skills. In the meantime, children's thinking was expected to develop spontaneously until, in high school and college, the subject-matter fields could become significant parts of the curriculum. But the development of many pupils did not keep pace with the school's expectations. They became frustrated by academic work and lost interest in education.

The older view of the development of children held that the early grades were, in part, a period of waiting for maturity. Today it is recognized in some quarters that intellectual stimulation during the formative years is as important as native endowment in determining the future achievement of each child. Such a view suggests that the elementary school make a greater, more vital contribution than merely communicating the three R's in rote fashion. This re-evaluation should in time affect all areas of the curriculum. However, its impact on mathematics and science programs is being felt earliest, though very slowly nevertheless.

Let me explain briefly how science is related to intellectual development. The present content of science consists of concepts and relationships that mankind has abstracted from the observation of natural phenomena over the centuries. This content is the outcome of a long, slow process. During the ele-



These fourth graders are measuring the location of a flag on their playground as part of the *Relative Position and Motion* unit. One boy is determining the direction with the aid of a sighting device on the ground, while the other is about to pace off the distance from the starting point.

mentary-school years, boys and girls are engaged in precisely the same kind of abstracting process with respect to their own natural environment. They accumulate experiences, and their thinking undergoes a gradual transition from the concrete to the abstract. Yet it has been found that there are many gaps and misconceptions in such spontaneously developed understandings.

One responsibility of the schools, therefore, is to guide the children's development by providing them with particularly informative and suggestive experiences as a base for their abstractions. At the same time, the children must be provided with a conceptual framework that permits them to perceive phenomena in a more meaningful way. This framework will also help them to integrate their inferences into generalizations of greater value than the ones they would form if left to their own devices.

The awareness of intellectual development just described is due in large part to the work of the Swiss psychologist Jean Piaget.¹ His ideas have been elaborated and applied to problems in education by American scholars such as Millie Almy,² Jerome Bruner,³ J. McV. Hunt,⁴ and Celia Stendler Lavatelli,⁵ among others. This school of thought has two related central ideas—that children's intellectual capacity passes through a number of qualitatively contrasting stages before adulthood, and that a child's interaction with his environment plays a very significant role in his transition from one stage to the next. [See the article by Piaget in this issue of PHYSICS TODAY.]

There is some variation from author to author in the specification of the suc-

cessive stages, but they all agree that children's modes of thinking differ drastically from those used by adults. Piaget,¹ for example, separates the development into four stages. Only in the last of these, called the stage of *formal operations*, does the individual reason about the relationships and implications of hypotheses as well as actualities. In the next-to-the-last stage, that of *concrete operations*, the person is able to reason by using operations, such as classification, serial ordering, and time sequencing, on objects, but he cannot yet apply such operations to verbally expressed hypotheses. Preceding this is a stage that is *pre-operational*: Objects exist and their present appearance can be described by the child, but changes with time or as a result of physical transformations are not comprehended by him. During infancy there is a *sensory-motor, preverbal stage* during which the permanent existence of objects and simple spatial relations are established through a combination of visual and kinesthetic explorations.

A few examples, which you may verify by working with children, will serve to illustrate this outline.⁶ Children who are unable to use "conservation" reasoning, for instance, are at the pre-operational stage: If liquid is poured from one container into another one of different shape, the pre-operational child responds that there is more in one than in the other; if a number of coins are rearranged from a long line into a circle or a heap, he says that there is a greater number in one arrangement than in the other.

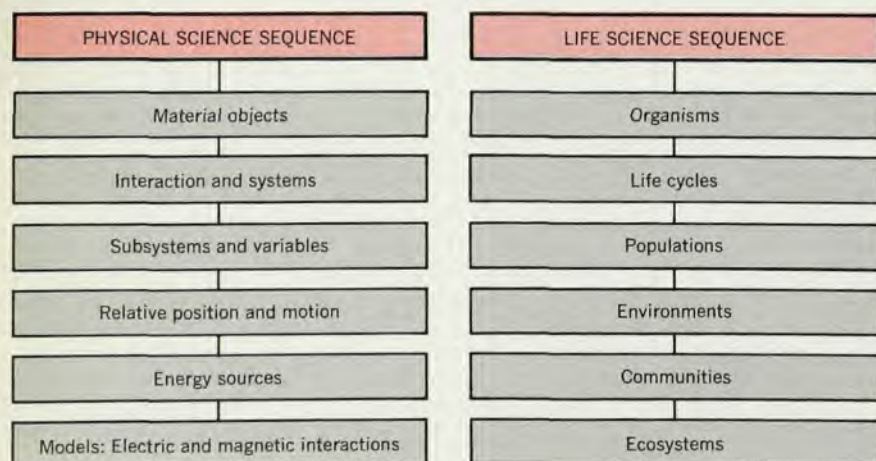
Children who can use conservation logic are at the stage of concrete operations. They recognize that an amount

or number stays the same if nothing is added or removed, even though its appearance changes. In other words, they recognize that the height of liquid in a narrow container may compensate for the width of the same amount of liquid in a wide container. They also serially order objects according to one property, and they know that if object A exceeds object B, and object B exceeds object C, then object A will exceed object C (transitivity). However, they are not yet able to reason about abstractions as effectively as they can reason about concrete operations. Even though they can divide a whole into parts ($1 \div 4 = \frac{1}{4}$), they cannot divide by fractions ($1 \div \frac{1}{4} = 4$), an operation that has no concrete analogue. Similarly, they cannot compare the energy of a heavy object a small distance above the floor and the energy of a light object a great distance above the floor. In other words, they do not recognize in what way energy is a composite of height and weight, even though they do recognize that the amount of liquid in a container is a composite of height and cross-sectional area.

The time of appearance of the stages varies with the individual. The pre-operational stage begins about age two; the stage of concrete operations, between five and ten; the stage of formal operations, between ten and fifteen. It is also known that an individual does not suddenly pass from one stage to the next. Instead, the development takes place in some areas first and then in others, so that a fifteen-year-old student may be in the stage of concrete operations with respect to the concept of ratio,⁷ but he may show formal thought in combinatorial reasoning (how many dress outfits can you make with two skirts and three blouses?).

To plan educational programs that advance children's intellectual development, one must know what factors influence it. Besides physiological maturation, on which the school cannot exert any influence, the two most significant factors appear to be self-directed physical and mental exploration of a rich environment and social interaction with parents, teachers and peers. The former nourishes the child's experience with regard to objects, phenomena, and the control the child can exert over them. The latter stimulates review of the experience and representation of it by words or symbols—both essential steps in dealing with abstractions. Of course, the level on which communication with others takes place must be appropriate to the developmental stage of the participating children. Hunt has summarized the situation in the following statement:

"The problem for management of child development is to find out how to govern the encounters that children



The Science Curriculum Improvement Study program for elementary-school children includes twelve interrelated units in the two sequences identified here. Each unit provides for the introduction of new concepts and the study of new phenomena through the children's own investigations. Figure 1



Magnetic field. This girl is sprinkling iron filings on a cardboard tray that conceals a small ferrite magnet. When her pattern is completed to her satisfaction, she will spray it with a transparent glue to fix it semipermanently for classroom display and comparison with the patterns produced by her classmates.



Melting ice. These boys have allowed warm water to interact with ice cubes in their foam plastic cups. They are determining the temperature and later will measure the amount of melted ice with the aid of the graduated vials. They will also compare the melting produced by one and two film cans full of warm water.

have with their environments to foster both an optimally rapid rate of intellectual development and a satisfying life."⁸

What about the often-heard recommendation that science instruction be postponed until the youngsters have reached the intellectual maturity of the middle teens? At this stage, unfortunately, educational efforts reach only the fraction of the student body that is favorably disposed toward science because of earlier positive experience at home or at school. For the others, many of whom form a strong dislike for science, it is too late. Their spontaneous intellectual development just does not keep pace with the expectation of the school, or does not proceed in the direction of modern science. As we know from physics enrollments in recent years, the eligible and interested group is very small.

The potential value of an elementary-school science program has been described by many educators who have concerned themselves with the broad objectives of science courses. Nevertheless, there is general agreement that cur-

rent teaching practices do not meet the pupils' needs. As Charles Silberman⁹ has pointed out, most schools put more emphasis on managing and controlling students than on challenging their minds or facilitating group activities initiated and planned by students. One great weakness of current practice, embedded in legislation in many states, is an excessive reliance on textbooks and other such authoritative sources of information. These sources for science learning are quite impotent compared to the direct experiences that nourish the pupils' intellectual development of "common-sense" rationality outside school. Instead of guiding this development in the direction of modern scientific understanding, therefore, the present-day science courses create a second, separate, relatively abstract structure of "book learning" which is not used outside the school situation and which eventually atrophies.

My remarks must not be interpreted to mean that a young student can learn only what he himself observes; the world is too complicated to permit that completely. It does mean, however, that the

early years of school should provide a highly diversified program based heavily on concrete experiences. The difficult part, which is often overlooked, is that the concrete experiences must be presented in a context that helps to build a conceptual framework, such as the interaction concept and its ramifications in physical, chemical and biological systems. Then, and only then, will the early learning form a base for the assimilation of experiences that come later—experiences that may involve either direct observation or verbal and pictorial reports of observations made by others. SCIS calls this functional understanding of scientific concepts "scientific literacy." It is the principal objective of the SCIS elementary-school science program.

Examples from SCIS

I have already implied that the actual form taken by the learning materials is as important for their effectiveness as their theoretical basis. The SCIS elementary-school science program is divided into twelve units, grouped into a physical-science sequence and a life-

This brain teaser was prepared for children of age 9 to 11 years studying the *Relative Position and Motion* unit. Before tackling it, the pupils measure distances in the classroom and on the playground. Figure 2

Brain Teaser

Paul and Bill were pacing distances.

Here are Paul's paces:



Paul counted 15 paces from the flagpole to the water fountain.

Bill counted 20 paces from the flagpole to the water fountain.

Which are Bill's paces?

Circle A, B, or C.

A 

B 

C 

Explain your choice. _____

science sequence (figure 1).¹⁰ Each unit is intended to sustain a teaching program for approximately one semester, but it may be extended or reduced depending on the time available for teaching science (usually one to two hours per week), the inclusion of optional activities, and the children's interest in pursuing investigations that they propose. The teaching materials for a unit include a teacher's guide, complete equipment kit, set of student manuals, and visual aids. (For more information enquire with the publisher¹⁰ or the author of this article.)

The children's activities in the early units are intended to stimulate concrete operational thinking. First graders, for instance, classify a highly diverse collection of buttons and experiment with floating and sinking objects; second graders observe schlieren when copper chloride dissolves in water and then recover the solid in crystalline form after the water evaporates (conservation of matter); third graders construct histograms to describe their data on the temperatures of water-ice systems and later speculate about the variables that may account for differences in motion of rotating systems powered by rubber bands.

The more advanced units, designed for the upper grades (pupil ages nine to twelve), are directed toward the beginning of formal thought. Beginning of formal thought is tempting for the teacher, who may very easily expect too much of his pupils. It has been difficult for the program developers at the SCIS to be realistic in their assessment of what most upper-grade students can do, just as it is difficult for high-school and college teachers to make this assessment of their students realistically. Because of the implications for later physics in-

struction, I shall now describe four activities taken from upper-grade units in considerable detail. Keep in mind that they should stimulate reasoning on the formal level, but that they must not frustrate the pre-operational students and the concrete-operational students who make up the majority in upper-grade classes.

1. A brain teaser included in the student manual for the *Relative Position and Motion* unit is reproduced in figure 2. Before encountering this challenge, the children pace the distances between objects on the school playground and make a crude "map" of the area. Note that the brain teaser not only requires an answer, but also an explanation of how the answer was found or is justified. Concern with such an explanation is important for logical development, for two reasons: First, it communicates to the learner the concept of an explanation that things happen for reasons and not capriciously and unpredictably; secondly, it makes the learner aware of his own thinking, a process he will have to control consciously if he is to carry out formal thought. In one class of fourth graders, about half of the students correctly chose answer C but only a few explained that more paces for the same distance meant smaller ones. Other students chose A, with the explanation that Bill has more, apparently identifying "more" paces with "larger" paces. A few students chose B and gave no explanation; they appear to have treated the brain teaser as a matching activity, which is the usual type of challenge they face in school work. Note that matching here is a perceptual task, since both sets of footprints are illustrated. The brain teaser is a conceptual task that requires reasoning about the unillustrated total distance. If the total dis-

tance paced and both boys' footprints were shown, the problem would be perceptual (counting paces).

2. In a laboratory-oriented program, the students' experimental accuracy is an important element. To allow useful inferences, experiments should be reproducible under classroom conditions when carried out with the equipment available and the care taken by the children. One investigation in the *Energy Sources* unit for fifth graders involves a comparison of the amount of ice melted when one or two cans of warm water are poured over two fresh ice cubes and five minutes of time elapses. Spilled water, variable waiting time, misread volume scales, and poking fingers all take their toll. Yet in one class in which ten teams of two children each performed this experiment, seven teams found a water ratio for two cans versus one can between 2.2 and 2.8 (theory might lead you to expect 2.0). The data are fairly consistent, but it is clearly impossible to base a mathematical model on such findings, much as a physicist might be tempted to introduce a heat of fusion.

What about thermal equilibrium in these systems? All twenty final temperatures clustered between 33°F and 42°F. Many children, however, expect that the temperature would drop further if they waited longer, and they believe that the time of interaction is the most important variable.

A brain teaser posed after the above experiment asked the children to predict the final water temperature and the amount of ice melted when three cans of about 110°F water are poured over two ice cubes and allowed to interact for five minutes. All children who responded predicted final temperatures near 40°, by citing the cooling in their own experiments. Only two, however, used their

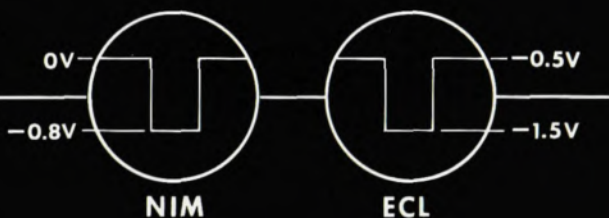
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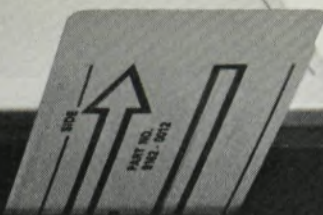
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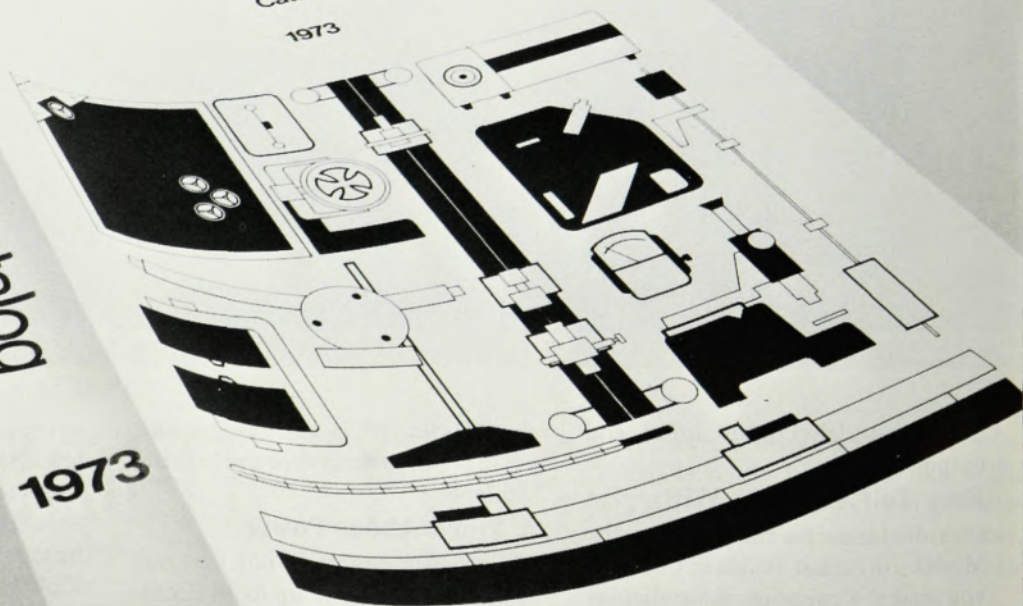
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data on the amount of water for the second prediction, one adding the observed amounts for one and for two cans, the other tripling his amount observed for one can of warm water. The others either gave no explanation, or said something like this: "I think that this is a good prediction. The hot water would melt the ice more if you add three cans of hot water."

3. The problem of experimental reliability also arises with sixth graders. In one activity in the *Models: Electric and Magnetic Interactions* unit, the children use a small Alnico bar magnet with ends painted red and yellow to label the pole faces of two rectangular ferrite magnets as follows: Put a red dot on the side that repels the red end and a yellow dot on the side that repels the yellow end. Thereafter they tested the interaction of the marked ferrite magnets. Twenty-two out of twenty-four children reported that red ferrite sides repel reds and attract yellows, while only two reported the opposite. When testing the painted Alnico magnets, all twenty-four reported the expected result. One may therefore conclude that the ferrite magnets were marked consistently with two exceptions.

4. After investigating the heating of nichrome wire in a circuit, and then the effect of varying the length in series or in parallel with a flashlight bulb, the sixth graders using the *Models* unit were asked how nichrome wire affects the electricity in a circuit. Of the twenty-one children who answered, five actually referred to electricity and wrote something like: "The electricity will travel through the shorter (nichrome) wire better than a long piece of wire." Ten children described their observations in clear general terms, such as, "If the wires are close together, the light is brighter, and when they are far apart it dims," but did not refer to electricity or energy transfer. Four children gave descriptions that were significantly less clear, and two children said there was no effect. Many students in this group gave more advanced answers than concrete operational pupils in other groups, who described their specific observations ("When I moved the wires apart, the bulb got dim"), but only a few were using the model introduced earlier, that electricity in the circuit accomplished the energy transfer.

I hope that these few activities, though taken out of their context in the SCIS teaching program, have communicated some of its scope, depth, and style. The qualitative activity (item 3) appears to have been more clearly successful than the quantitative investigations in the other examples. At least that is the way I react, with my standards of experimental accuracy. And the same impression has been conveyed

by many other examples: Most children are imaginative and comprehensive in qualitative descriptions (when testing a wire coil in an intermittently closed circuit with a magnet, children wrote, "It feels like a heart beat and I can feel vibrations most of the time"), but their interest and care ebb to low levels when numerical data are to be analyzed.

The implication is that children, even eleven- and twelve-year-olds, are not mature scientists, nor graduate students, and that the values they take from an activity are not the same as a scientist would derive. Yet this does not mean the activity is "wasted." Children need intellectual stimulation at their level, and that level will differ widely among the students of one elementary-school class. In choosing the specific materials, the children's reasoning, manipulative ability, preconceptions and natural interests were taken into account, as well as questions, of safety, cost and equipment reliability.

My present feelings about the SCIS learning materials are that they represent a challenging resource for teachers and children. I do not think of them providing a universal "teacher-proof" learning experience, whereby every participating child develops the same scientific knowledge, understanding, and attitudes according to the stated objectives. Instead, each teacher and each pupil will make use of the materials in his own way, with many common elements but also with some unique aspects. Each teacher, I hope, will be able to conduct a program that is somewhat richer in providing experiences, insights and intellectual challenges than the same teacher would conduct without these materials.

High-school and college science

The study of intellectual development and its relation to elementary-school science has important consequences for science instruction at higher levels. It is clear from work with college students and adults that their ability to reason on the formal level is rarely adequate to encompass the results or thinking or attitudes of modern science.¹¹ This is not surprising, because few schools give systematic attention to activities requiring reasoning and explanations. High-school and college students can be divided approximately into two groups—a small number who have developed formal thought structures and can use the mathematical-scientific reasoning required in physics and chemistry courses, and the majority who have not developed formal structures and therefore can study science effectively only if they begin with the concrete materials that are also appropriate for pupils at the upper elementary school. In other words, "beginners" in physics must start with certain experiences and simple concepts

regardless of their age or educational level. Even adults entering a new field of endeavor often pass through a concrete stage as they familiarize themselves with its rules and procedures.

Unfortunately, many physics instructors appear to be very reluctant to provide instruction for beginners. Instead, they view themselves as dealing primarily with the few elite students who have successfully made the transition to formal thought. Two among the many obstacles for less-advanced students are the lack of qualitative laboratory work that might broaden their intuition and the emphasis of the Newtonian theory of motion to which I already referred at the beginning of this article.

Let me give a few examples from my own teaching experience to substantiate this claim. One nonscience student, about to measure the temperature of warm water in a cup, carefully shook the small thermometer, then placed it in the water for two minutes, and finally picked it up and held it by the bulb while reading the scale. Another student complained that an experiment with ice and water didn't work, because "the (Fahrenheit) thermometer was stuck at 33° as long as there was ice left, and only went up after it had all melted." Many freshmen in a calculus-based sequence were greatly confused by a rectangular ferrite magnet whose pole faces were on the wide sides. They could not reconcile their observations of a compass needle and of iron-filing patterns near this magnet with their expectation that the poles were at the magnet ends. (Though more verbal in their distress, they did not progress as far as the sixth graders who labeled the pole



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faces of the very same magnets successfully.) Some students in the same class appeared unable to solve problems that require more analysis than substitution of numbers into a memorized formula. Surely these observations are not unique, though they may be embarrassing to an instructor at the University of California!

I believe that most of us have closed our eyes to the actual level of student understanding in our classes. We have allowed the rapid progress of a few learners—those using formal thought in Piagetian terms—to overshadow the difficulties of the many. Most of the new secondary-school courses primarily serve this special population. New college-level sequences are even more demanding. Selection rather than education of students has been the result.

Very recently a more tolerant attitude has become noticeable. Community college teachers in particular try to reach their students at the level where they are, rather than wishing they were more able. A few texts such as *PSNS, An Approach to Physical Science*,¹² the college-level *Introductory Physical Science*,¹³ and *Introductory Physics, a Model Approach*¹⁴ present a conceptual structure and related investigations more appropriate to beginning students. Take-home laboratories for beginners are being developed to circumvent the lack in facilities at many schools.¹⁵ The special needs of prospective teachers, many of whom are themselves beginners and will have to face beginners in their work, are beginning to be recognized.¹⁶ And the Council on Physics in Education of the American Association of Physics Teachers has recently called for a special effort to meet the needs of non-specialist students of all ages.

You may wonder whether programs designed for concrete operational students can develop formal thinking at the senior high school or college level. I am not aware of any work in this area, but I believe that progress can be made once the problem is recognized rather than being ignored. That is one of my current interests. Yet I also believe that a sound and challenging elementary-school program will help greatly in this task, for it significantly extends the period of time during which development is stimulated.

What can you do?

In concluding this article, I should like to appeal for assistance. Improved scientific literacy is a must if mankind is to achieve a consensus on the compromises that are necessary if we are to benefit from technology while maintaining a habitable ecosystem. Educational institutions as well as mass media have to contribute. Use your special knowledge and understanding to participate in this gigantic task. You might contact the

schools or colleges in your community to find what physics or science they offer for beginners, you might encourage them to make use of some of the new curriculum materials that have become available, you might offer to assist their teachers in what may be a very difficult task, you might invite beginning students to learn about your laboratory, you might write nontechnical articles concerning your area of work for students or wider audiences, or you might (if you are in a fortunate position) provide financial assistance for innovative educational efforts.

* * *

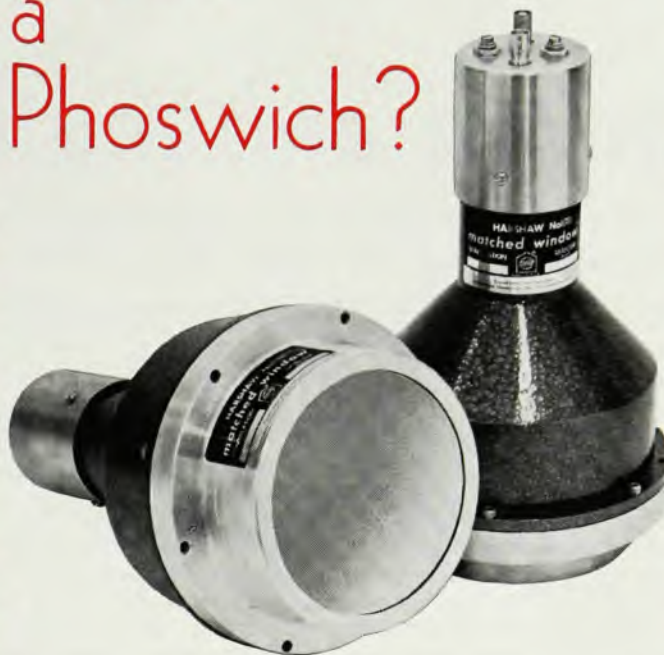
The development of the SCIS materials has been supported by grants from the National Science Foundation.

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