(In: *The Physics Teacher*, April 1979, pp235–242.)

Wherefore a science of teaching?

David Hestenes

David Hestenes is professor of theoretical physics at Arizona State University. He was motivated to pursue physics by undergraduate studies in philosophy. Consequently, he has been concerned with analyzing the conceptual structure of physics and mathematics from the beginning of his career. This is reflected in his research publications in relativistic quantum theory and other topics. (Department of Physics, Arizona State University, Tempe, Arizona 85287-1504.)

Teaching, I say, is an art, and not a science. . . in no sense can teaching be said to be a science. These words, written by F. K. Richtmyer in 1933[1] were recently reiterated in this journal by R. A. Goodwin.[2] Professor Goodwin seems to think that all the *great truths* about teaching are already known, so that recent attempts to improve teaching techniques can hardly be more than transitory "fads." I am sorry to see someone who is concerned with the quality of teaching take such a divisive stance. Perhaps a reply will help some readers develop a more constructive point of view.

I will argue that an ample foundation for a science of teaching exists already today, but that the "science" remains in a primitive state primarily because it has not been fostered and cultivated by those in a position to do it, namely, the university professors.

Art or science?

Let us agree at the outset that *good teaching is an art*, fully deserving our respect and admiration. It does not follow, however, as Goodwin seems to think, that there cannot also be a *science of teaching*. Who will not agree that there is an art of experimental physics and an art of mathematical thinking? Nobody, let us hope, confuses the art of doing science with the body of knowledge which it produces. Nor should anyone confuse the teaching skills acquired by individuals with an objective body of knowledge about teaching. Medical practice is widely acknowledged to be an art, but who doubts the possibility of medical science? Is teaching so different because it ministers to the mind?

Goodwin would have us believe that because good teaching is an art it is hardly susceptible to rational analysis. He says, "I cannot define it, nor can I establish exacting criteria for it." He claims, nevertheless, to have an unerring eye for good teaching, and he recommends *The Art of Teaching* [3] by Gilbert Highet as an account of "good teaching as it is and as it should be." Highet's book is a treasury of pedagogical folklore and rules-of-thumb. Much of it should be taken to heart by every earnest teacher. But much else shows how desperately we need established facts and a viable theory of the learning process. For example, Highet contends[4] (rightly, I think) that "the best way to know one's pupils is to divide them into types." Unfortunately, the best classification he can recommend is Sheldon's theory of body types and temperaments. We can do very much better today. As we shall see, it is possible to classify students according to fairly well-defined reasoning patterns they employ, and this has implications for the way we should go about teaching them.

Since teaching ministers to the mind, a science of teaching presupposes a science of thinking. In 1933, when American psychology was dominated by a cognitively impoverished behaviorism, Professor Richtmyer could justifiably doubt that there was any such science. But the situation has since changed dramatically, as reference to a good textbook[5] in educational psychology will show. Let us review some major developments of particular relevance to teaching.

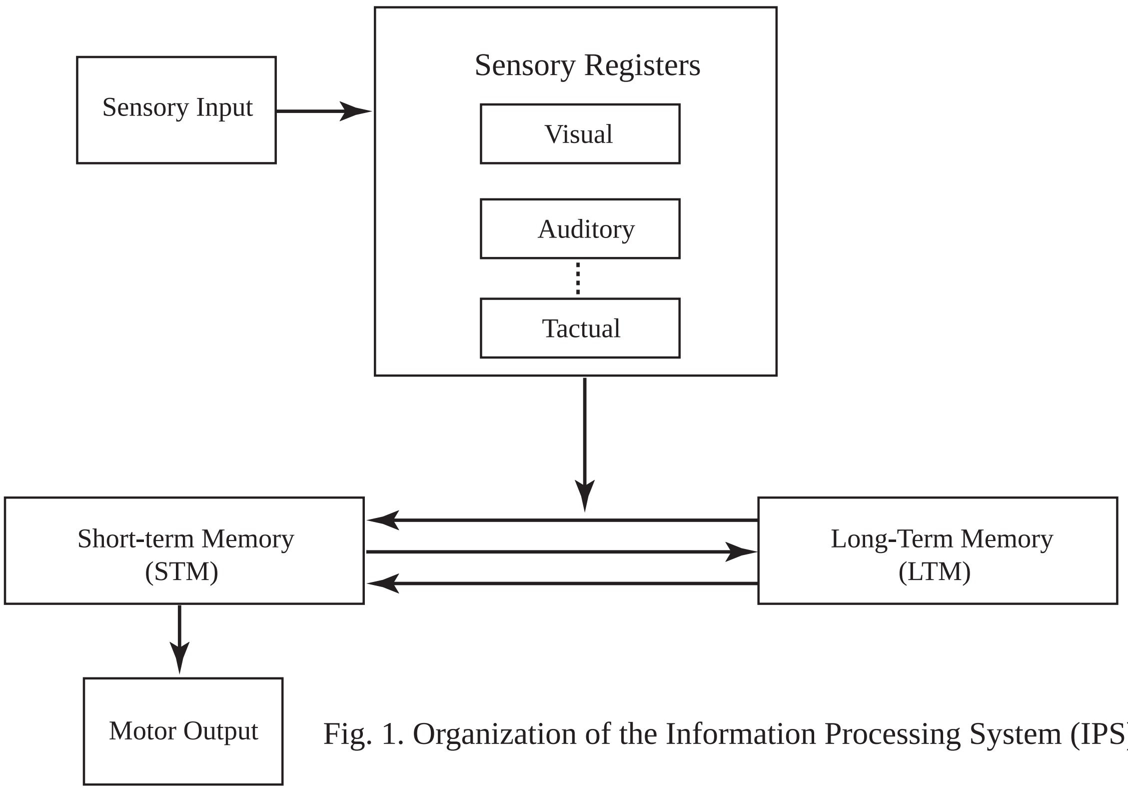

Fig. 1. Organization of the Information Processing System (IPS).

The science of thinking

The science of thinking is generally known as *cognitive psychology*. Physicists who have hardly stepped out of their own discipline, especially those over 50, may have some doubt that cognitive psychology qualifies as a science, so I hope to convince them that the discipline has some nontrivial facts and theoretical constructs to offer.

In the last three decades cognitive psychology has undergone a major revolution in several directions at once. I wish to call attention to progress along two lines in particular: (1) the development of information processing theories and (2) the consolidation of developmental psychology. It cannot be overstressed, however, that there is much research along other lines with important implications for a science of teaching. Cognitive psychology is in a period of great ferment and rapid development, with diverse schools and research programs from which, nevertheless, the outlines of a comprehensive theory of cognitive processes has begun to emerge.

Information processing

Models of a thinking human being as an *Information Processing System* (IPS) have evolved alongside the modern computer. Both the computer and the human being can be regarded as different species of the genus IPS. Both can *operate* on *input* with a well-defined symbolic structure to produce an equally well-defined *output*. The performance of each is determined by its *hardware* (physical structure) and its *software* (programming). Comparison of the two kinds of systems has vastly improved our understanding of both. On the one hand, the power of computers has steadily increased with attempts to program them to duplicate the processing powers of humans *(Artificial Intelligence).* On the other hand, computer science has developed a language that makes it possible to describe the processing powers of humans with a precision previously unknown to cognitive psychology. This has stimulated new theories and research into the structure of the human IPS. Much of the theorizing has been disciplined by the stringent criterion that the description of a human processing capability be regarded as satisfactory only to the extent that it enables one to simulate the process on a computer. Computer simulation has proved to be a powerful method for comparing theory with data and generating new predictions.

The literature on human information processing is vast. Fortunately, there is a single book which provides both a unified view of the field and an example of the best in theory and experiment. I refer to *Human Problem Solving* by Allen Newell and Herbert Simon.[6] The theory developed in this book is intimately related to work for which Simon recently received the Nobel Prize. It is hard to imagine how anyone acquainted with this monumental treatise could maintain that cognitive psychology is unable to provide a foundation of nontrivial fact and theory for a science of teaching. The book is packed with facts and ideas that throw light on the problem-solving process in science and mathematics. But, more than that, it develops a model of the human IPS with a wider educational significance. Let us examine some salient features of the model.

The general structure of the human IPS is indicated in Fig. 1. Philosophers had identified its major components long ago by introspection. Thus, the old concept of consciousness refers to the *Short-Term Memory* (STM) while the *Long-Term Memory* (LTM) had been identified as an unconscious component of mind. These components of mind can now be described with some precision and detail, thanks to a variety of ingenious experiments devised by psychologists. Here are a few important facts about the components in Fig. I that are fairly well established.

The sensory registers retain information for about one second. More precisely, information has a lifetime of about 1/2 sec in the visual register and 3 to 4 sec in the auditory register. Recognition time in the visual register is 30 to 40 msec (milliseconds). Recognized items are transferred to the STM after being coded by a program in the LTM.

The STM has capacity of only 5 to 7 symbols, or *chunks* as they are often called. The chunks are units in a code determined by programs in the LTM. The chunks may designate letters, words, things, or conceptual units of arbitrary size and complexity.

Little information remains in the STM for more than 30 sec unless it is retained by *rehearsal* (an overt or covert repetition) or some other process. It may be that information in the STM decays, but the principal mechanism for information loss is replacement of old chunks by new chunks. Information lost from the STM is lost forever. All this is consistent with the familiar experience that you will forget the name of someone to whom you have just been introduced unless you use it within the next 10 to 15 seconds.

The LTM has a capacity which is infinite for all practical purposes, since there is no evidence that it is filled in a lifetime or that information in it is lost. However, most of the information in the LTM is inaccessible at any given time. Chunks can be transferred from the STM to the LTM by rehearsal with the slow *write-time* of 5 to 10 sec per chunk, and only one chunk can be transferred at a time. On the other hand, the LTM has a *read-out time* of a few hundred milliseconds per chunk. This may be compared with a read-out time of 10 to 30 msecs for the STM. Chunks transferred to the LTM are more easily retrieved if they are associated with verbal or visual images.

All the familiar cognitive processes such as remembering and various kinds of reasoning begin with inputs from the STM and end with outputs in the STM. The most elementary processes, such as comparison and replacement of symbols, take about 40 msec. More complicated processes are composed of elementary processes done in *series*, one at a time. Consequently, the difficulty of such processes as multiplying three digit numbers "in your head" stems from the small capacity of the STM and the slow write-time of the LTM.

The facts we have just reviewed, particularly those about the operation of the STM, have many significant educational consequences. Teachers continually overload the STM's of their students and wonder why the students don't get the message. Recently, a colleague of mine was disgusted with the students in his class because none of them seemed capable of performing a simple arithmetic calculation to evaluate a formula they had been discussing. I explained to him that psychologists had shown that mental arithmetic will obliterate the contents of an STM in less than 30 sec,[7] and they sometimes use it for just that purpose. Consequently, any student who carried out the proposed calculation probably lost track of the original problem or the reason for doing it. In a good piece of education research, Mary Budd Rowe found that teachers seldom wait much longer than one second for responses to their questions.[8] From the facts about IPS processing times we know that it would be impossible to get a thoughtful answer within this time interval except from a student who had one already prepared in his STM or indexed for rapid retrieval from his LTM.

The facts about STM should be a big help to the teacher trying to help students make effective use of their *external memory*, namely, books, paper and pencil, blackboard, and other visual aids. Newell and Simon show that control of the STM is an essential feature of any effective problem-solving strategy. Such control must be equally essential to any process of learning or communicating. Students need to learn how to use paper and pencil to control their thinking as well as to express their thoughts. And teachers need to learn how to teach them to do it.

So far we have considered only "hardware facts" describing general capabilities of the human IPS. To be sure, the real hardware is the brain, but neuropsychology and physiology have a long way to go before they can explain the properties of thinking in terms of neuronal processes. Indeed, progress is likely to continue in the other direction for some time, with the facts about cognitive processes guiding investigations into the structure and operation of the brain. This has been the direction of development in physics, where *macroscopic* laws and equations of state served as guides to the discovery of atoms and their properties long before they could be explained and derived from *microscopic* properties by statistical mechanics. The point is that the "hardware facts" we have discussed are just as "hard" as facts about neurophysiology, and they are a lot more useful for characterizing cognitive processes.

Performance of the IPS depends on its *software* as much as its hardware. The software consists of *programs* written in the LTM, the programs which determine how input to the IPS is encoded and processed. The hardware is determined by heredity, but the software is developed from experience in a very complex way. Obviously, the distinction between hardware and software is crucial for theories of learning and instruction because it is needed to distinguish that which can be taught from that which cannot. The hardware-software distinction is an improvement over the classical nature-nurture distinction because it is backed up by a theory of information processing which makes it more precise and useful.

As in a computer, all programs in the LTM must be composed of certain elementary processes such as writing, holding, comparing, and replacing symbols. The elementary processes and their processing times are certainly determined by the hardware. But it may well be that the organization of the elementary processes into complex programs is determined entirely by experience. There is no doubt that humans possess a self-programming mechanism which is operative from birth.

In opposition to this theoretical stance, it might be objected that some students are obviously brighter than others, that some have a natural ability for science while others do not. However, information processing theory provides a framework for a more discriminating analysis of the facts. It is undoubtedly true that some people can process information more rapidly than others because their hardware is better, although, like height and weight, the STM capacity and the various process rates cited earlier do not vary much over a population of normal healthy adults. This "hardware effect" may be quite obvious in simpler processes such as rote memorization or arithmetic computation. But for complex reasoning processes, the organization of the program and the structure of subroutines is more important than processing time. Everyone who has written a computer program knows that a desired result can be achieved by programs differing widely in efficiency, and that the smallest flaw will cause the entire program to fail. One can imagine many reasons why a person with perfectly good hardware may fail to develop some of the more complex programs. For example, he may have developed a program for one of the essential subroutines which floods the STM so it cannot be integrated into more complex programs. Surely, if addition is programmed as counting on fingers, it will be difficult to learn long multiplication. We cannot unravel the complexities of intelligence here. I only wish to make the point that intelligence may depend more on software than hardware, so it may be more amenable to teaching than generally believed. The central problem for a theory of instruction is, then, to learn how to program the human IPS efficiently.

Developmental psychology

Jean Piaget is the Charles Darwin of developmental psychology. He gave the subject its first comprehensive theory of cognitive growth and compiled a mountain of facts to support it. Piaget's theory is no more the last word on cognitive growth than Darwin's theory was the last word on evolution. But it is too firmly anchored to be upset by armchair critics like Ralph Goodwin. Only solid scientific work can improve and extend Piaget's theory. His theory has undergone surprisingly little modification while being assimilated into American psychology during the last three decades.

Information processing theory and developmental psychology are two of several different research traditions in American psychology. They involve different people who use different methods, publish in different journals, and are often located in different departments within a university. To some extent the two traditions are concerned with complementary aspects of cognition, but the overlap is considerable so it is desirable to integrate them into a unified theory.[9] For this reason, I shall use the conceptual framework of information processing theory to describe and interpret some major features of Piaget's theory.

The relevance of Piagetian theory to physics teaching is nicely brought out in a recent AAPT workshop[10] developed under the leadership of Robert Karplus. As some "academic scofflaws" like Ralph Goodwin have missed the major points of the workshop entirely, I will try to clarify those points by expressing them in different terms. But let it be understood that there is much more to Piagetian theory than is mentioned here or in the workshop. Those who want to know the important details of Piaget's theory and experimental approach should consult one of his many major works[11] or the account of a competent interpreter.[12]

Piaget describes cognitive development from birth to adulthood as the acquisition of an increasingly complex system of reasoning patterns or *schemes* as he calls them. Each scheme is a program in the LTM available to process information presented by experience. To identify and classify schemes possessed by an individual, Piaget has developed an interview technique and a number of carefully designed reasoning *tasks* to be used as probes. There is far more to be learned from an interview than the success or failure of an individual to complete a given task. The skillful interviewer will learn details about how the problem is attacked, what given information is deemed essential or overlooked, how the individual responds to hints, and so on. Piaget has examined children of all ages by this method, accumulating a vast store of information which provides the empirical base for his theory.

Piaget has identified a sequence of four major stages or *levels* of cognitive development, called the *Sensorimotor*, the *Preoperational*, the *Concrete Operational*, and the *Formal Operational* level. Each level is characterized theoretically by a set of specific cognitive processes and empirically by a set of Piagetian tasks to detect those processes. For example, processes characterizing the Concrete Operational level include classification, seriation, all the operations required for the concept of number, and fundamental operations in the elementary logic of classes and relations. The Formal Operational level is characterized by more complex processes such as isolation and control of variables, proportional reasoning, and propositional logic. The processes characteristic of each level incorporate and integrate processes from the preceding level, so it is not surprising that cognitive development has been observed to progress sequentially from one level to next. However, the mere fact that such development occurs at all has many implications for teaching.

Teachers should become sensitive to the cognitive levels of their students, so they can *match* their methods to the capabilities of their students. They should become adept at recognizing reasoning skills required to process written materials and complete assignments so they can anticipate where students are likely to have difficulty. Most students in high school and college reason at the concrete or formal level, so it is especially important for science teachers to recognize the role of concrete and formal processes in understanding science.

At this point we should be sure to dispel the common misconception, shared by Professor Goodwin, that Piaget's distinction between Concrete and Formal thought is equivalent to the common distinction between concrete and abstract concepts. There is nothing more abstract than the number concept, which is quite within reach of the Concrete thinker. Formal operations differ from Concrete operations in their complexity rather than their abstractness, as one can see by examining the Piagetian tasks used to test for them. However, there is also an important qualitative difference between Concrete and Formal thinking: Formal thinkers are able to analyze their own reasoning quite explicitly. Such analysis may well facilitate the formation of Formal operations. For this reason, teachers should strive to help students become aware of their own reasoning patterns.

To determine specific educational implications of Piaget's theory, we must examine the role of specific reasoning patterns in learning. Surely proportional reasoning is one of the most important reasoning patterns in science; one can hardly get started in physics and chemistry without it. It is commonly believed that proportional reasoning is taught in high school algebra courses when students are introduced to the formula a/b= c/d. On the contrary, Piaget's theory implies that a student cannot comprehend the formula unless he is already capable of proportional reasoning. Proportional reasoning is carried out by programs in the LTM which coordinate a system of functional relations. No programs, no reasoning. Inhelder and Piaget have developed a sensitive test for proportional reasoning using balancing tasks.[11] A student who completes the tasks successfully has a well-defined "intuitive understanding" of proportions though he may not know how to express a proportion with algebraic symbols.

Empirical studies show that the majority of American high school students reason at the Concrete level.[13] How do such students cope with high school algebra? Since they do not possess the conceptual structures needed to fully understand algebraic symbolism, they must resort to alternative strategies such as rote memorization. It is to be expected, then, that their abilities to recall and handle algebraic relations will decline rapidly after they have completed the course. The relation of cognitive level to long-term retention of algebra has not been systematically studied, but science teachers continually encounter students who seem to remember nothing at all from their high school algebra courses. It is hard to escape the conclusion that conventional high school algebra courses are a total waste of time for Concrete thinkers. This is not to say that Concrete thinkers cannot learn algebra, but only that they need instruction to help them develop formal operations.

Formal operations are obviously essential for understanding science. Yet available evidence shows that science courses do little if anything to help students acquire them.[14] Rather, science courses tacitly select the Formal thinkers and discourage the Concrete thinkers by continually confronting them with information which cannot be processed without Formal operations. The social cost of this selection process is enormous, as evidenced by widespread fear and antipathy toward science among those who have been selected out by befuddlement.

The Piagetian perspective suggests that a central goal of introductory science courses in high school and college should be to raise the reasoning skills of all students to the Formal operational level. This goal will be difficult to reach. It is attainable in principle, however, if the Formal thinker is distinguished from the Concrete thinker by superior software rather than hardware, as our preceding analysis suggests. Even so, it will be necessary to devise effective teaching strategies based on some understanding of how reasoning processes are programmed in the LTM. Inadequate as our knowledge is about these matters, enough is known to suggest a promising course of action.[9]

It is fairly well established empirically that a Concrete thinker cannot be taught proportional reasoning or any other formal operation simply by explaining or demonstrating how it is done, no matter how lucid, detailed and patient the presentation.[15] The traditional teaching methods of explaining and demonstrating may be effective methods for information transfer, but only if the student possesses the schemes needed to process the information, and they evidently do little to promote the development of such schemes.

Piaget has theorized that cognitive growth is generated by a process called *equilibration* or *self-regulation.* Self-regulation is a kind of problem-solving process whereby a person resolves discrepancies in given information to produce a self-consistent representation of the information in the LTM. This suggests that teachers can facilitate cognitive growth in their students by confronting them with problems which they cannot solve without self-regulation and guiding them to a successful resolution of discrepancies. All this is easier said than done. The AAPT Workshop proposes a three-stage teaching strategy based on the concept of self-regulation. But miraculous improvements in teaching effectiveness are neither promised nor expected, and the whole matter deserves a lot more research.

Educational research

In our brief review of cognitive psychology we have noted several steps that the individual science teacher can take to improve his effectiveness. He can further refine his insight into the teaching process by becoming familiar with research journals such as *Science Education* and the *Journal for Research in Science Teaching*. However, the teaching effectiveness of an individual is limited as much by the state of his profession as by his own ability and initiative. The teacher can no more develop effective new curricula and teaching techniques on his own than he can discover *ab initio* the basic principles of the science he teaches. If the profession of teaching is ever to transcend the folklore state of Gilbert Highet, it must be guided and supported by a program of profound educational research.

What should be the domain of science education research? It should embrace at least the following three kinds of activities:

(1) Structural analysis. The structure of science must be analyzed from both logical and psychological points of view to identify the essentials that need to be taught and what it takes to understand them. Cognitive growth is a process of progressive differentiation and integration of mental structures (schemes). Accordingly, scientific knowledge must be organized into a series of well-defined levels of increasing complexity and sophistication if it is to be taught efficiently.

(2) Methodological analysis. The development and the application of science requires a variety of problem-solving techniques. The problem-solving strategies used by scientists must be identified and classified before they can be taught systematically. It is especially important to distinguish strategies with broad applicability from special techniques devised for particular problems. A study of problem solving in mathematics has been made by Polya,[16] but without attention to the psychological aspects considered by Newell and Simon. There is no comparable study of problem solving in physics or any of the other sciences.

(3) Curriculum development. To be maximally effective, science curricula must be *designed* in accordance with sound scientific and psychological principles. The design must include teaching strategies as well as the selection and organization of subject matter; it must be concerned with the details of student and teacher activities. A specific curriculum is a kind of instructional model; it must be *tested* and compared with alternative models to determine its adequacy.

As formulated here, science education research is obviously an interdisciplinary enterprise, so a few remarks on the roles of various disciplines are in order.

A structural and methodological analysis of science should certainly be classified as philosophy of science. The philosophers have much to say about this. However, they have not developed an integrated view of the logical and psychological components or carried out the analysis in the detail that is necessary to determine its educational implications. The details cannot be worked out without the insight of the scientist and the psychologist, but they cannot be coordinated without a broad philosophical perspective. In educational applications philosophy of science may find the relevance to scientific activity that it has lacked in the past.

We have seen that cognitive psychology has much to offer, but much less than what is needed for a satisfactory theory of scientific thinking. The teachers can't wait for a better theory, nor should science education researchers leave the development of such a theory up to the psychologists. Scientists and science teachers know a great deal about effective reasoning strategies that has not yet been incorporated into psychological theory. Indeed, the main ingredients of Piaget's theory are concepts which have been taken over from biology, mathematics, and physics. Physics is ideal for studying reasoning and learning strategies because the subject matter is well-defined and the concepts involved vary widely in kind and complexity. It would be most difficult for a psychologist to acquire the scientific insight needed for a deep study of scientific thinking. It is easier for a scientist to learn the relevant results and methods of psychology. Science education research is needed to link psychology with the natural sciences.

Mathematics has been called "the language of science." A science can certainly not be separated from its language. The cognitive processes in science have so much in common with those in mathematics that it would be foolish not to integrate research in science education with research in mathematics education. Yet this is the foolish state of affairs that prevails today.

High quality research in science education is difficult to achieve. Few individuals have the broad competence in science, mathematics, psychology and philosophy coupled with the experience in teaching that such research requires. The research must therefore be a cooperative effort involving individuals with a wide variety of backgrounds. Because the research is so difficult the bulk of it must be carried out or directed by well-trained specialists. Such specialists exist and they have formed a professional society, the National Association for Research in Science Teaching. Unfortunately, most of these specialists are located in schools of education so they are cut off from the well-spring of their discipline, the various scientific disciplines themselves. Consequently, their research suffers in quality, and is limited primarily to the teaching of science to young children. Science education research will not come of age until it is recognized and actively supported in the universities by departments of physics, chemistry, biology, and mathematics. Unfortunately, there is not much reason to expect that such recognition and support will soon be forthcoming.

The quality of science teaching

The standards of science teaching are set by the university professor who, in principle at least, divides his time equally between teaching and scientific research. The professor writes the textbooks, develops and directs the college science curriculum, and trains the elementary and high school teachers in science. Indirectly or directly the university professor is responsible for the quality of science teaching at every level from kindergarten through graduate school. If science curricula and teacher training are to be improved, the professor must lead the way, for only he has the necessary resources: the insight into the structure and content of science, control of teacher training in science, and the resources for instructional research and curriculum development. I am sorry to say that the professor has hardly recognized his responsibility, let alone fulfilled it with much distinction. Let us review the record.

The professor frequently complains about the weak background in science and mathematics which his students bring from high school, but how much of the fault is his own? The high school science teacher is generally required to have a college major in science, so he gets his training from the professor, who makes little effort to see that it is appropriate. To absolve himself of responsibility for proper teacher training, the professor has assented to an unnatural division of the curriculum into *content* and *method*, with the professor supposedly teaching science *content*, while the school of education teaches teaching *method*. The poor student is left with the impossible problem of adapting and uniting these fragments into an effective high school teaching strategy. Little wonder that the typical high school science course is hardly more than a "watered down" version of a college science course. True, special blue-ribbon committees of university professors have been assembled from time to time to create new high school science curricula, but these efforts are sporadic and they have produced little improvement in instructional strategies, so it should not be surprising that their effect has been minimal.

On top of this, the entire high school curriculum as well as all efforts at curriculum reform are seriously hampered by the division of science into disciplines. There are good reasons for this division in the universities, but none at all in the high schools. At the high school level, the principles and objectives of physics and chemistry have so much in common that it is arbitrary and foolish to separate them. Yet chemistry teachers are not prepared to teach physics, and physics teachers are not prepared to teach chemistry. Nor does it make sense to maintain a rigid separation between mathematics and its applications in high school. Yet many high school math teachers are pitifully ignorant of math applications, as are some of the math professors who trained them. If the teachers can't make the connections, how can the students be expected to do it? What will it take to get professors of physics, chemistry, and mathematics to cooperate in the training of teachers?

The available science curricula for elementary school are much better than those for high school. Unfortunately, even in elementary school the science and math curricula are as rigidly separated as disciplines in a university. The math curriculum has only recently recovered from the disastrous "New Math" program. The responsibility of university professors for the New Math fiasco has been documented by Morris Kline.[17] In contrast, some excellent science curricula[18] have been developed under the leadership of university professors with the wisdom to pay attention to the advice of experienced teachers and the insights of Piagetian psychology. Still, these curricula have been adopted in only a small minority of the schools, and most university scientists are not sufficiently well informed to push for reform of science teaching even in schools attended by their own children, because their profession has held itself aloof from the problem. At the university, the scientist need not be directly involved in the training of teachers to recognize the obligation of his profession to see that it is done well, but few take this obligation to heart, and teacher training suffers on account.

The generally unsatisfactory condition of science teaching and curricula in the schools reflects the condition of science teaching in the universities. The distinguished mathematician Morris Kline has published a scathing critique of teaching by mathematics professors.[19] Much the same could be said about professors in other disciplines. One does not have to look closely to identify the prevailing attitude in the universities. Though teaching and research are said to be of equal importance, mediocre research consistently gets more academic rewards than good teaching. Graduate teaching assistants seldom get more than minimal training and supervision. At the national level, creation of the Science Education Directorate of the National Science Foundation was initiated by Congress, which is evidently more aware of its importance than the scientists. Congress has repeatedly tried to upgrade science education, with less than enthusiastic support of the scientists, and the scientists in control of the NSF have continued to treat the Science Education Directorate as a weak stepchild.

For the typical professor, teaching is an affair between himself and the blackboard. If he succeeds in expounding his subject in a manner that is clear to himself, he considers his duty done. He is faintly aware that the students cannot follow even his most brilliant lectures and explanations any better than he can follow the typical unintelligible colloquium presented by his colleagues. But it is painful to see how badly the students perform, and it is a bother to correct their mistakes, so he does it as little as possible.

Anyway, he is satisfied that the gifted students, the ones that matter, will master the subject in the end just as he had done.

Given his conception of teaching, there is little wonder that the professor has such a low opinion of it. After all, "anyone can teach who knows the subject and takes the trouble to work up a decent set of notes." The "good teacher" is more popular with the students, because he likes to show off and perhaps hobnob with them, but where is the evidence that he teaches them more? The professor knows that he learned very little from all those lectures he attended as a student; he knows that his own competence came from hard work he did on his own. Good students like himself learn the subject no matter how it is taught if only they are directed to the right books. These are the students who succeed in the university science curricula.

Besides informal anecdotes from professors, we have seen that there are good psychological reasons to believe that the lecture method is not an effective way to teach what is most important. Why, then, does the professor rely so heavily on lectures? Chances are he hasn't thought much about the matter and doesn't want to. He lectures because that is what professors do. No one has proved that there is a better method of teaching. There certainly isn't an easier one. Best of all, by preparing and giving lectures the professor comes to learn the subject he didn't quite get right as a student. He finally learns the answers to some of the questions that used to bother him. These make good examination questions.

Attempts at educational innovation are more likely to be penalized than rewarded in a university. The professor's idea of innovation is an occasional new topic or new course. His reaction to anything beyond this is typified by Goodwin's article. Goodwin cannot find anything good to say about the recent innovations in physics teaching which he attacks. His criticism of the Personalized System of Instruction (PSI) is directed primarily at the outmoded behaviorism often used in its design, and secondarily at some of its practical drawbacks, of which all practitioners are well aware. It is indeed unfortunate that most physics professors are unaware that behaviorism has long been abandoned by educational psychologists, at least since Noam Chomsky's devastating critique of B. F. Skinner's major monograph *Verbal Behavior*.[20] However, behaviorism is not essential to PSI.

There is considerable evidence that PSI is superior to conventional methods of instruction,[21] at least for certain purposes. The strength of PSI is its student-centered approach, as opposed to the *teacher-centered* approach advocated by Goodwin. PSI aims to get the student actively engaged in working with the subject matter, rather than passively hearing about it. Consequently, PSI is more dependent on good written materials and student activities than the lecture method. The materials that are available are inadequate, and it is too much to ask a teacher to develop them himself. The potential of PSI cannot be realized without a program of systematic educational research. Since the universities do not have such programs, we should not be surprised that PSI courses have only a short lifetime in spite of their successes. The effort required, the lack of appreciation, faculty apathy and even opposition all contribute to the demise of PSI courses, and undoubtedly to other educational innovations as well.

Professor Kline[19] concludes that competition with research in the universities is so detrimental to teaching that he recommends that the two functions be physically and financially separated by setting up research institutes. I suggest that the development of a sound program of educational research would be much more beneficial to teaching. Such a program would not only improve teaching theory and technique, it would make clear what competencies are required of a good teacher and help professors attain them. Educational research should be required to meet the same standards as scientific research, but it cannot be raised to those standards without comparable support and commitment. Competent educational research is no more a part-time activity than competent scientific research. The relatively trivial educational research so common in the universities is an inevitable consequence of trivial commitment by the universities. Rather than belittle such research, the professors have an obligation to see that it is upgraded. Let no one think that educational research is easy; it is concerned with no less than unraveling the complexities of the human mind. There is no reason to believe that an effective theory and technology of instruction is any easier to achieve than controlled nuclear fusion. It is certainly every bit as worthy.

1. F. K. Richtmyer, *Am. J. Phys*. **1**, 1 (1933). This article has been reprinted in *Phys. Teach*. **14**, 30 (1976).
2. Ralph A. Goodwin, *Phys. Teach*. **16**, 367 (1978).
3. Gilbert Highet, *The Art of Teaching*, (Alfred A. Knopf, New York 1950).
4. Ref. 3, page 40-45**.**
5. Sylvia Farnham-Diggory, *Cognitive Processes in Education*, (Harper and Row, New York, 1972).
6. Allen Newell and Herbert Simon, *Human Problem Solving* (Prentice-Hall, Englewood Cliffs, NJ, 1972).
7. R. C. Atkinson and R. M. Shiffrin, *Sci. Amer*. **225**, 82 (1971).
8. M. B. Rowe, "Wait-Time and Rewards, Their Influence on Language, Logic, and Fate Control." *J. of Res. in Sci. Teaching*, **3**, 12 (1965).
9. For a review of important recent work integrating information processing theory and Piagetian psychology into a united theory of learning and instruction see the article by Robbie Case in the forthcoming Seventh Yearbook of the Association for the Education of Teachers in Science: *The Psychology of Teaching for Thinking and Creativity,* Anton E. Lawson, editor (scheduled to be available in March 1979).
10. *Workshop on Physics Teaching and the Development of Reasoning*, American Association of Physics Teachers, Stony Brook, New York.
l l. B. Inhelder and J. Piaget, *The Growth of Logical Thinking from Childhood to Adolescence* (Basic Books, New York 1958).
12. J. H. Flavell, *The Developmental Psychology of Jean Piaget*, (Van Nostrand, Princeton, NJ 1963).
13. A. E. Lawson and J. W. Renner, "A quantitative analysis of responses to Piagetian tasks and its implications for curriculum," *Science Education* **58** (4), 545-559 (1974), E. L. Chiapetta, "A Review of Piagetian Studies Relevant to Science Instruction at the Secondary Level and College Level," Science Education, **60** (2), 253-262 (1976).
14. A. J. D. Black and Floyd H. Nordland, "Science Instruction and Cognitive Growth in College Students," *J. of Res. in Sci Teaching*, **15** (5), 413420(1978); R. J. Bady, "Effect of Taking Science on Formal Logical Reasoning Abilities," Paper presented at the NARST Annual Convention, March 1978.
15. For teachers who are interested in strategies to teach proportional reasoning, I recommend: A. E. Lawson and W. T. Wollman, "Developmental Level and Learning to Solve Problems of Proportionality in the Classroom" *School Science and Mathematics*, in press; B. A. Kurtz, *A Study of Teaching for Proportional Reasoning*," unpublished doctoral dissertation, University of California, Berkeley, 1976; R. W. Peterson, 1. Collea, E. Streitberger and S. Nummendal, "Proportional Reasoning at the University Level: Alternative Approaches to Task Analysis and Teaching," Symposium at the NARST Annual Convention, 1978.
16. G. Polya, *How To Solve It* (Princeton, NJ, 5th printing, 1978); *Mathematics and Plausible Reasoning*, 2 Vol., (Princeton, NJ, 1975).
17. M. Kline, *Why Johnny Can't Add*. (St. Martin's Press, New York 1973).

18. One of the best elementary science curricula is the Science Curriculum Improvement Study developed under the direction of physicist Robert Karplus, Lawrence Hall of Science, Berkeley, California.
19. M. Kline, *Why the Professor Can't Teach*, (St. Martin's Press, New York 1977).
20. N. Chomsky, Language 35, 26-58 (1959); reprinted in *The Structure of Language*, J. Fodor and K. Katz, editors (Prentice-Hall, Englewood Cliffs, New Jersey, 1964).
21. T. Taveggia, *Am. J. Phys*., **44**, 1028 (1976).