Physics teaching: Does it hinder intellectual development?

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A necessary condition for effectively teaching physics is that the students have the capability of operating at the cognitive level that is matched with the logical structure that produced the discipline. Recent research indicates that a majority of students are not demonstrating this capacity. The analysis of the performance of students "learning" physics without the necessary cognitive development demonstrates behavior that hinders their intellectual growth.

SCIENTIFIC THINKING AND COGNITIVE DEVELOPMENT

The sophomoric view of science, as often presented in introductory texts, implies that outcomes of the scientific enterprise are simply the deductive results obtained from experimental observations. I cannot accept this view of the nature of science in light of the challenges against it by many persons in diversified fields. Thomas Kuhn, in *The Structure of Scientific Revolutions,* states[1]:

> . . . the aim of such books [classics and texts] is persuasive and pedagogic; a concept of science drawn from them is no more likely to fit the enterprise that produced them than an image of a natural culture drawn from a tourist brochure.

Furthermore, Jean Piaget argues, "The fundamental vice of such empirical interpretation is to forget the activity of the subject." Rejecting the notion that the union between experiment and deduction is sufficient for scientific understanding, he concludes[2]:

> . . . a collaboration [must exist] between the data offered by the object and the actions or operations of the subject—these actions and operations constituting the limit beyond which the subject is never able to assimilate the object.

The quotation is representative of the Piagetian frame, in which the focus is shifted from the object to the actions and operations of the subject. It is this change in emphasis that makes Piagetian psychology analogous to Kuhn's views in which he describes the actions and operations of the scientific community struggling to develop its paradigms. Kuhn is not talking about the object of the endeavor, the physical universe, but the values, techniques, and operations shared by the members of the community of science in the process of creating its gestalt of that universe.

Gerald Holton echoes this position in his recent book, *Thematic Origins of Scientific Thought: Kepler to Einstein,* as he defines[3]:

> . . . the crucial distinction between two different activities—related to each other and with a fuzzy border between them, but still quite different—that are nevertheless denoted by the same term science. One is the private aspect, science in the making, . . . the other is the public aspect, science as an institution.

Thus, the disciplines, as presented in introductory texts, should not be viewed as the deductive results of empirical observations and experimentation. They are the outcomes of interactions between the scientists in the role of subjects and the physical universe as the object. The dynamic component of the encounter is the application of the existing paradigms.

The outcomes of these interactions, the laws, the theories, and the statements of conservation, which constitute the domain of public science, as presented in our elementary texts, are defined, structured, and delimited by the encounter. From this perspective, I believe, the enterprise of science can be characterized as follows: the physical universe assumes the role of an object to be operated upon by the applications of the paradigms; the subject of this interaction is the scientific community.

The role of the scientific group as subject is most important because its members are not drawn at random from the general population, but from a well-defined community of the scientist's professional compeers. Thus, the operations that define and delimit the structure of public science may not be shared by the population as a whole.

Figure 1 schematically represents the position stated above. Scientists assume that an external physical universe exists independently of science and investigate portions of it. Inputs are received from this universe and are operated upon by the current paradigms of science; then public science, the accepted laws and theories, emerges. Feedback between the paradigms and public science is continually interacting with inputs from the physical universe, and the potential for growth and self-correction is

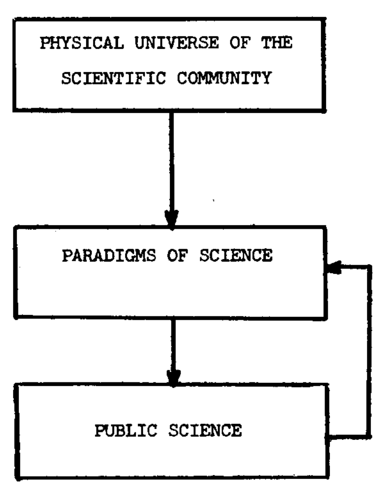

Fig. 1. Structure of scientific enterprise.

present.

If I apply the object–interaction–subject argument to the enterprise of science education, then public science is the object and the students that are the subjects are the source of the dynamics of interaction. Assigning the role of object to the domain of public science is most important because this object is distinctly different from that of the scientific community. Public science is a new entity, created by the interaction between the paradigms and nature. It has been processed, structured, assimilated, and then stated as a representation of the physical universe.

Many members of the scientific community, especially those engaged in the educational component, assume the new product to be real and self-evident. This ambiguity of object between the physical universe and public science has presented a perplexing problem to authors of texts. The first chapter of the book, *Physics, An Exact Science,*[4] is entitled, "The Limitations of Measurement." The disclaimers in the problem sections provide additional evidence: "in the absence of forces," "if there is no slipping," "provided there is no rotation," and the most popular, "assuming no friction."

The philosophical view of science posited by Kuhn and others has as its analog in psychology the Piagetian concept of development. In the latter, it is the individual "acting upon" his environment, assimilating, accommodating, and tending to a state of stable equilibrium. The individual also experiences the struggle of revolution as he evolves through the stages of development: sensorimotor, preoperational, concrete operations, and formal operations.

Figure 2 shows schematically the Piagetian developmental process in parallel to that of science. Again it is assumed that an external physical universe exists independent of the individual. The person's awareness of the dimensions of the field may overlap that of the scientific community as indicated by the cross-hatching. The diagram is not intended to imply the existence of two separate physical universes, but to emphasize the role of the observer. Inputs from the world are never passively received. The available structures and the current paradigms sensitize the receptor to unique aspects of the gestalt. These inputs are then acted upon and there emerges a new world view which may be significantly different from the initial input. The outputs of the dynamic processes of both branches of the diagram are defined and delimited by the actions and operations performed upon them.

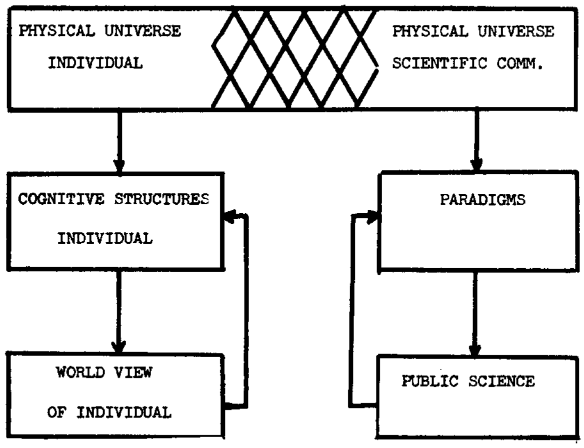

Fig. 2. Parallel structures.

An analysis of the individual's branch of the diagram can be described in Piagetian terminology as assimilation, accommodation, and equilibration, where assimilation refers to the selective reception of inputs, accommodation to the changing of the cognitive structures, and equilibration to the dynamic process of growth. The final integration is the state of the individual's world view.

To maximize the educational experience of an individual, in my opinion, a necessary condition must exist: the cognitive structures of the learner must be similar in form to the logical structures of the processes that produced the discipline. Since the paradigms that produced classical physics are relatively constant, variables in the educational process must be examined and they are the cognitive structures of the students.

I postulate that the cognitive operations, described by Piaget's stage of late formal development,[5] best match the structures of the paradigms which produced the physical sciences. This stage of development is characterized by the individual's ability to reason about propositions considered to be pure hypotheses. The capability exists to produce the realm of possibilities and to perform the reversible transformations that are the hall mark of hypothetico-deductive reasoning.

The basic premise underlying college science instruction, which is instruction in public science, is the assumption that students are fully capable of operating at the level of formal operational thought by the time they enter college. Therefore, they are competent to act as subjects in an analogous role to the "scientist's professional compeers."

COGNITIVE LEVELS OF THE STUDENT POPULATION

I found that a sizable portion of the student population is, in fact, not operating in the domain of formal thinking and that their cognitive structures are best characterized as being in the concrete operational stage or in the process of transition. This means that many students cannot separate an argument or logical organization from its content.

The students are operating in a world "that is" and not a world "that could be." Therefore, they do not think in terms of ideal states, limits, or infinitesimals, the keystones of scientific thought.

The introductory science courses are thus a source of potential conflict between the logical structures of the discipline and the cognitive development of the student. Public science is the culmination of actions and operations that parallel the characteristics of formal thinking. If the students have not achieved this level of cognitive development, the possibility of significant learning is greatly reduced.

A number of recent research results tend to confirm the hypothesis. Kuhn, Langer, Kohlberg and Haan[6] in an experiment to assess the presence of formal operational thought structures in normal adolescents and adults reported that at least 60% of the college age population did not achieve the criteria.

In another study, Schwebel[7] tested approximately 60 randomly selected Rutgers University freshmen, utilizing Piagetian tasks, and reported a mean score below the level of formal thinking. Schwebel's work was corroborated by Keasey[8] using similar tasks with women subjects at Trenton State College.

Another work, authored by McKinnon and Renner,[9]

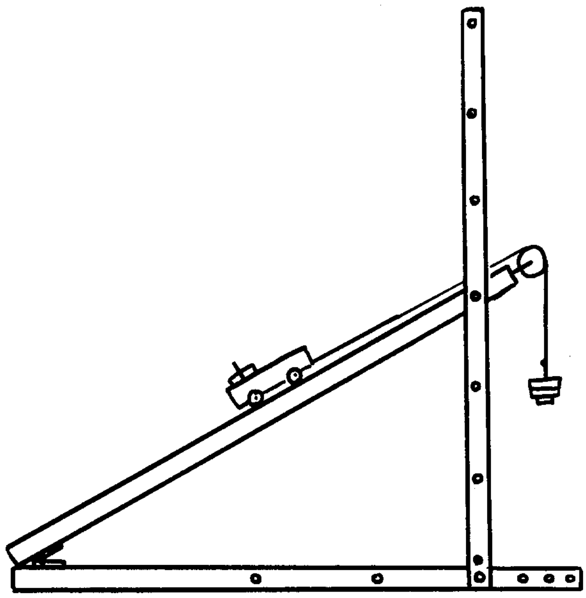

Fig. 3. Schematic representation of plane.

used freshmen subjects at Oklahoma City University and found that approximately 25% of the sample population were operating in the formal domain.

In my work,[10] not only were the general findings confirmed, with only 39% of the population functioning at the stage of formal operations, but no significant differences were found between white and minority students.

A very significant additional result emerged from the analysis of the responses of the students that were tested with a Piagetian equilibrium problem. The task was to predict the movements or equilibrium of a skate on a variable-slope inclined plane. The last variable must be calculated not in terms of the direct measurement of the angle but in terms of its sine: the ratio of the vertical height of the plane to the constant length of the plane.[11]

Figure 3 is a representation of the experimental equipment. The length of the plane is the same as the length of the base. The distance between the extreme holes in the supporting rod is also the same length since both the plane and the base and the holes are equally spaced. There are dowels spaced along the base and at the end of the plane that allow the support rod to be placed in a vertical position if the subject so chooses.

The experimental equipment was presented to the subjects and its operation was explained. I then set the plane at an arbitrary position and put the skate in a state of equilibrium. The subjects were asked first to identify the variables that were involved in keeping the skate in equilibrium and secondly to determine a relationship between them. All suggestions and conclusions could be experimentally tested, and the subjects were urged to make maximum use of the equipment. I willingly served as an assistant, and every effort was made to maximize their performance. The experimental sessions were recorded on tape, and detailed notes were assembled for independent analyses.

As a final test of the subjects' grasp of the variable-slope task, the skate, when in a state of equilibrium, was displaced up or down the plane and the individuals were asked to predict what would happen when it was released. This is the only procedure which was employed that was significantly different from the original experiment described by Piaget.

Table I. Population parameters.

	Rutgers subjects (N=30)		Essex subjects (N=30)	
	Male	Female	Male	Female
White	25	3	11	1
Minority	2	0	16	2

The subjects tested in the experiment, $N=60$, were randomly selected from second semester physics and chemistry courses at Rutgers University and from nontransferable developmental science and physics courses at Essex County College in Newark. Most participants were male and the major difference, other than the level of the courses, was that the majority of the Essex component was black, as is shown in Table I.

ANALYSIS OF RESULTS

The taped responses obtained from the participants of the plane task were analyzed according to two criteria: (1) student's understanding of the problem as described by Piaget's stage of formal thinking, and (2) the level of technical vocabulary utilized by the subjects in response to the experimental situation. A limitation of the first criterion is the fact that only one task was given to determine the stage of cognitive operations of the subject. Thus, no claim about the individual can be made because if other tasks had been given the results could have been different. However, the results can be interpreted as representative of a class of individuals. The second criterion, the level of technical vocabulary, was determined by the usage and frequency of terms such as component, tension, equilibrium, summation, torque, sine, slope, work, friction, ratio, and proportion. Although this determination is fundamentally subjective, it was very clear from the context of usage that some subjects interpreted the experiment as "science" and applied their vocabulary from that frame.

Each subject was ultimately assigned to one of the four following classifications based on the two criteria:

$$\text{Formal} \times \text{Technical},$$

$$\text{Formal} \times \text{Nontechnical},$$

$$\text{Nonformal} \times \text{Technical},$$

$$\text{Nonformal} \times \text{Nontechnical}.$$

The experimenter and independent judges reviewed the data, and a summary of the distribution of the subjects is shown in Table II.

Table II. Classification matrix.

	Rutgers subjects (N=30)		Essex subjects (N=30)	
	Formal	Nonformal	Formal	Nonformal
Technical	30%	55%	10%	23%
Nontechnical	4%	11%	17%	50%

Subjects in the Formal × Technical group were the quickest to respond to the problem. They had an excellent command of the vocabulary; therefore, they were well aware of its range and limitations. Typically, they would refer to friction, tension, mass of the cord, and the role of the pulley, but immediately disregarded them when assured they could be neglected.

When confronted with the problem of not being able to directly measure the angle, the search for a related variable began. Actual experimental manipulation was limited. Each operation was done with purpose, a hypothesis to be tested.

The second group, Formal × Nontechnical, labored under the handicap of not possessing the words needed to express their understanding succinctly. However, their ability to improvise produced phrases that could be described as "poetry of physics." For example, one subject, attempting to explain the rôle of the incline stated:

> The grams on the skate and the grams on weight don't equal out and stopping there would defy the law. So the position of the plane is needed.

Seeking to explain that an increase in the height causes the force component of the skate to increase, the response was:

> Since moving it up causes the skate to weigh more, that means I need more weight to balance it out.

The term equilibrium was transformed into "balance them off period." The concept of all things being equal was interpreted as "or else we'll be all screwed up." Finally, the concept of limiting evolved as, with the height at five-sixths, "it was two-thirds and up there they are equal, so it's between two-thirds and one."

A second characteristic of this group was the subjects' ability to respond to experimental evidence. When their predictions were contradicted, they immediately corrected their intuitive answers and proceeded with the new information. This group experimented a great deal more than the Formal × Technical subjects, but indicated by their behavior that they had an objective. The final characteristic of this group, much like the first, was the tendency to utilize the questions of the experimenter to further the development of the solution of the problem.

The third group, Nonformal × Technical vocabulary, contained the widest range of responses. Because of the limitations of the classification matrix, the level of understanding varied from the domain of early formal operations to early concrete operations. The characteristics described are representative of the middle range of subjects with the extremes demonstrating similar traits but correspondingly scaled.

The striking characteristic of the Nonformal × Technical vocabulary cell is the faith these students have placed in their vocabulary. In many instances, when a conflict was apparent between the predicted results and the experimental evidence, a technical term was imposed to explain the discrepancy. For example, when the skate was in equilibrium, the experimenter moved it to a new position on the track and asked what could be expected when it was released. A subject responded: "It will go back because the torques must be equal." When confronted with the lack of movement, "that's because of friction," was the answer. Another replied to the same situation with, ". . . because of activation energy, the skate will return to the equilibrium position." Again, responding to the evidence, the response was: "Give it a push. If the forces are balanced it will keep moving back and forth until it reaches the limit." Following the directions given, the exchange was ended with the final disclaimer, "friction is preventing it."

It was the same characteristic, dependence upon vocabulary, that limited the manipulations by the group. Typical was the response of one subject to attempts by the experimenter to have him utilize the vertical limit. Refusing to add weights to balance the skate, the following was the reply: "You have to calculate it. You must set all the forces equal to zero, then sum all the forces acting on the body equal to zero, then solve it for what it really means." We never found out what weight was needed, and the subject argued that weight had to be greater than the weight of the skate.

Another characteristic of this class was the inability of the subjects to utilize the questions of the examiner. This trait prevented many of the subjects from changing their focus from the angle, as the critical variable, and seeking an alternative. A typical response was: "Without the angle, no relationship can be found." Suggestions made to encourage manipulation of the equipment were answered from the framework of vocabulary. The experimental spirit was lacking, and often the investigators were given the impression that the equipment was a necessary evil.

The final category, Nonformal × Nontechnical, exhibited the same range of success as the previous group and thus the limitations of interpretation must apply. The major handicap of this class of subjects was their inability to improvise expressions to communicate their findings. Lacking the organization of the Formal × Nontechnical subjects, information was obtained but not acted upon. This characteristic was similar to the Nonformal × Technical, except they had no words to call upon.

The Nonformal × Nontechnical group did manipulate the equipment much more than the two technical groups but each experiment was a separate entity, no plan or objective was evident. The questions of the investigator were received and acted upon, but not in relationship to what the subject had experienced or what was to follow.

The ending of a test session shed further light on differences among the groups. The two formal groups actively pursued a general relationship and were not content until they found it to their satisfaction. The two nonformal groups were distinctly different. The technical subgroup was willing to end at anytime. They felt they possessed the answer very early in the operation; hence, continued manipulations only further contaminated their understanding. The nontechnical subgroup became passive and typically the question was posed: "What else do you want me to do?" The collection of unrelated details seemed to become over burdening and fatigue was evident.

IMPLICATIONS FOR PHYSICS EDUCATION

From the educational perspective, the data of this experiment are indicative of a need to redefine the fundamental problems of science education. The argument that has been developed can be summarized as follows:

(1) The contents of the introductory science courses

are the product of the paradigms interacting with inputs from the physical universe.

(2) These paradigms exhibit the dynamic characteristics of Piaget's formal stage.

(3) A large proportion of the student population is either in the concrete stage of operations or the process of transition.

(4) The mismatch of the structures of public science and the student's cognitive development render an otherwise effective method of education impotent.

Furthermore, it must be emphasized that no significant difference, in terms of Piagetian development, was found between the populations from which the Rutgers and Essex samples were drawn. In technical vocabulary, however, the Rutgers students were much more proficient, with only 15% classified nontechnical, while 67% of the Essex students were so classified.

On the basis of the experimental data, it can be concluded that screening methods employed at both institutions are not designed to identify the presence of formal operations, but that Rutgers does seem to select for technical vocabulary. It should be noted that all but one of the Essex students who scored in the stage of formal operations were rejected when they applied for admission to local four-year colleges.

The first step which must be taken by the science educational enterprise is to understand that it is not facing a simple two-celled problem. This work indicates that a minimum of four cells must be recognized, each with its own special educational problems.

It is to the first cell, Formal × Technical, that the physics educational community has historically directed its efforts. These students not only possess the necessary cognitive level of functioning, but in all probability can demonstrate the skills and techniques that are regarded so highly by the profession. Students representative of this classification have been and will be actively sought by the physics community.

The second group, Formal × Nontechnical, provide a unique problem. These students possess the necessary cognitive development but are lacking the accepted proficiency in vocabulary and/or mathematics skills. It is most probable that this type of student would not be admitted directly to a university level program.

Assuming that the individuals do find entrance into a program, the educational problems posed by this group have been efficiently solved. Audiovisual materials, programmed instruction, and the Keller plan can effectively build the vocabulary and skills that are prerequisites for entrance into a transfer course.

Students falling into the third cell, Nonformal × Technical, present a totally different problem. They have probably experienced success in the educational domain, working hard to master words and skills that have little meaning to them, but receiving passing grades that allow them entrance into the next level. Much of the educational technology produced during the past decade has been directed to serve their apparent needs, yet with possibly counterproductive results.

The interpretation of the data of this experiment indicates that these efforts to meet the demands of the students may be detrimental. The product of formal operations, public science, cannot be indefinitely superimposed upon a nonformal cognitive structure. The students' defense against the imminent collapse of their reasoning was evident in the experiments. They rejected physical inputs and retreated to their vocabulary: words not fully understood.

This type of response effectively removes the students from the intellectual encounter and stymies the potential for growth. It is not that they are passive to inputs, but rather that they reject them. In essence, the subjects are superimposing a poorly understood formal interpretation of the physical universe onto a concrete problem to which it is mismatched, and they reject all evidence that indicates the error. The interaction is not dynamic but conservative, a condition that will tend to hinder their intellectual growth.

The final category of students, Nonformal × Nontechnical students, is discriminated against the most. Not only are these students laboring under the handicap of limited cognitive development, but their lack of proficiency in the skills and techniques required to gain the rewards of higher education has branded them as failures.

The current educational response to the needs of this class has as its objectives the development of skills and vocabulary criteria established by the technical group. To this goal remedial courses are directed; the students are drilled, tutored, and trained. The total resources of the educational enterprise are devoted to the cause: instructional objectives are written; educational technology (the tape recorders, the projectors, the computers, the programmed materials) lends it support; and dedicated teachers give their time and energy. Yet their nonformal reasoning patterns persist unchanged.

If the students can withstand the onslaught of educational technology, and if the remedial efforts are successful, what is the product? It would seem to be a "literate," nonformal individual who may be certified by society, but is still burdened with a serious handicap.

I believe that the focus of higher education must be shifted from literacy to cognition. The primary goal of instruction must be directed to moving the students from the domain of nonformal thought to formal operations. Once this has been achieved, the further progress from nontechnical to technical promises to be relatively simple.

[1]T. Kuhn, *The Structure of Scientific Revolutions* (University of Chicago, Chicago, 1970), p. 1.

[2]J. Piaget, *Psychology and Epistemology: Toward a Theory of Knowledge* (Viking, New York, 1971), p. 87.

[3]G. Holton, *Thematic Origins of Scientific Thought: Kepler to Einstein* (Harvard University, Cambridge, MA, 1973), p. 15.

[4]H. White, *Physics, An Exact Science* (Van Nostrand, New York, 1960).

[5]For a detailed description of formal thought see J. Piaget and B. Inhelder, *The Psychology of the Child* (Basic, New York, 1969), pp. 130–151.

[6]D. Kuhn, J. Langer, L. Kohlberg, and N. Haan, Columbia University International Scientific Research Pool Grant, Monograph No. 5S05, RR07060-05, Scope Q, 1971 (unpublished).

[7]M. Schwebel, U.S. Department of Health, Education, and Welfare, Office of Education, Bureau of Research, Final Report Project No. 0-B-105, Grant No. OEG-2-7-0039(509), 1972 (unpublished).

[8]C. Keasey, Dev. Psychol. **6**, 364 (1972).

[9]J. McKinnon and J. Renner, Am. J. Phys. **39**, 1047 (1971).

[10]D. Griffiths, doctoral dissertation, Rutgers University, 1973 (unpublished).

[11]For details of the experiment, see B. Inhelder and J. Piaget, *The Growth of Logical Thinking From Childhood to Adolescence* (Basic, New York, 1958), pp. 182–198.