Guest Comment: How we teach and how students learn—A mismatch?

During the past 15 years, a steadily increasing number of physicists have been contributing to the growth of a new field for scholarly inquiry: the learning and teaching of physics. We have by now a rich source of documented information in the many published reports of this research. At this point, it seems reasonable to ask whether we have learned anything from this collective experience that would be useful in current efforts to bring about innovative reform in the introductory course. Results from research indicate that at all levels of instruction the difference between what is taught and what is learned is often greater than most instructors realize. This discrepancy suggests the following question: Is there a corresponding mismatch between *how* we teach and *how* students learn?

I. TRADITIONAL APPROACH TO INSTRUCTION

Instruction in introductory physics has traditionally been based on the instructor's view of the subject and the instructor's perception of the student. Most teachers of physics are eager to transmit both their knowledge and enthusiasm. They hope that their students will acquire not only specific information and skills but also come to appreciate the beauty and power that the physicist finds in physics. Having obtained a particular insight after hours, days, months, or years of intellectual effort, they want to share this knowledge. To save students from going through the same struggles, instructors often teach from the top down, from the general to the particular. Generalizations are often fully formulated when they are introduced. Students are not actively engaged in the process of abstraction and generalization. Very little inductive thinking is involved; the reasoning is almost entirely deductive. By presenting general principles and showing how to apply them in a few special cases, instructors hope to teach students how to do the same in new situations.

In recalling how they were inspired by their own experience with introductory physics, many instructors tend to think of students as younger versions of themselves. In actual fact, such a description fits only a very small minority. Typically, in the U.S., no more than one in every 30 university students taking introductory physics will major in the subject. The trouble with the traditional approach is that it ignores the possibility that the perception of students may be very different from that of the instructor. Perhaps most students are not ready or able to learn physics in the way that the subject is usually taught.

II. SOME GENERALIZATIONS ABOUT LEARNING AND TEACHING

The generalizations that appear below are based on results from research on the learning and teaching of physics.[1] The evidence presented in support of the generalizations is taken from the cited articles on research by the Physics Education Group at the University of Washington. However, the same arguments could be based on findings by other investigators.[2] Similar conclusions have also been reached by experienced instructors who have probed student understanding in less formal ways in the classroom.[3]

A. Facility in solving standard quantitative problems is not an adequate criterion for functional understanding. *(Questions that require qualitative reasoning and verbal explanation are essential.)*

The criterion most often used in physics instruction as a measure of mastery of the subject is performance on standard quantitative problems. As course grades attest, many students who complete a typical introductory course can solve such problems satisfactorily. However, they are often dependent on memorized formulas and do not develop a functional understanding of physics, i.e., the ability to do the reasoning needed to apply appropriate concepts and physical principles in situations not previously encountered. We illustrate this first generalization with examples from dynamics and electricity.

1. Example from dynamics: impulse-momentum and work-energy theorems

In an investigation conducted several years ago, we examined whether students could apply the impulse-momentum and work-energy theorems to a simple motion that they could observe.[1,4] The motion was generated by applying a constant force to two objects of different mass over the same distance. Students were asked to compare the final momenta and kinetic energies of the objects. No calculations were needed to predict that the heavier object would have a greater momentum and that both would have the same kinetic energy. It was only necessary to understand the relationship between impulse and momentum and the relationship between work and kinetic energy. For a response to be considered correct, both the right comparison and the proper reasoning were required.

Data were gathered in individual demonstration interviews. The 28 students who participated came from two classes: an honors section of calculus-based physics and a regular section of algebra-based physics. Responses ranged from random formula searches to conscious attempts to apply the theorems. Only a few honor students were able to give satisfactory answers initially. With step-by-step guidance, most of these students eventually succeeded. Even with help, however, virtually no one in the algebra-based course was able to apply the concepts of impulse and work to make a correct comparison. There was a similar lack of success when written versions of the tasks were presented in a regular section of calculus-based physics. Among the many errors was the failure of most students to recognize the cause-and-effect relationships inherent in the theorems. Some seemed to treat the symbol "=" as if it represented only a mathematical relationship in which the variables may take on any values, provided the equality is maintained.

2. Example from electricity: electric circuits

We have been investigating student understanding of electric circuits over a period of several years.[5] One task that has proved particularly effective for eliciting common difficulties is based on three simple circuits consisting of identical bulbs and ideal batteries. One circuit has a single bulb; another has two bulbs in series; the third has two bulbs in parallel. Students are asked to rank the five bulbs according to relative brightness and to explain their reasoning. This comparison requires no calculations. A simple qualitative model, in which bulb brightness is related to current or potential difference, is sufficient.

We have administered this task to more than 500 university students. Almost every possible bulb order has appeared. Whether before or after instruction, only about 15% of the students in a typical calculus-based course give the correct ranking. We have obtained the same results from high school physics teachers and from university faculty who teach other sciences and mathematics. Many people who are unable to rank the bulbs properly can use Ohm's law and Kirchhoff's rules to solve more complicated problems. Evidently, success on standard problems is not a reliable indicator of functional understanding.

B. A coherent conceptual framework is not typically an outcome of traditional instruction. *Students need to participate in the process of constructing qualitative models that can help them understand relationships and differences among concepts.*

Perhaps the most serious difficulty that we have identified is failure to integrate related concepts into a coherent framework. Rote use of formulas is common. To solve standard problems, mathematical manipulation may suffice. To be able to apply a concept in a variety of contexts, however, students must not only be able to define that concept but also relate it to others. They also need to differentiate that concept from related concepts.

The question on ranking the bulbs was first administered several years ago on a course examination in a standard calculus-based course. Lacking a conceptual model on which to base predictions, most students relied on intuition or formulas. About 40% used algebra to find the equivalent resistances of the series and parallel circuits, substituted the values into the formula for the power dissipated in a resistor, and associated the results with the brightness of individual bulbs in the series and parallel networks. Such errors revealed a failure to differentiate between two related concepts: the resistance of an element and the equivalent resistance of a network containing that element.

A general instructional strategy that we have found useful for helping students relate electrical concepts and distinguish one from another is to engage them actively in the intellectual process of constructing a qualitative model for an electric circuit. Development of the model is based on observations of the behavior of batteries and bulbs, preferably through experiments that the students themselves perform.

Experience has shown that emphasis on concept development and model-building does not detract from performance on quantitative problems. Many students need explicit instruction on problem-solving procedures to develop the requisite skills. However, once equations are introduced, students often avoid thinking of the physics involved. Postponing use of algebraic formalism until after a qualitative understanding has been developed has proved to be an effective approach. Although less time is spent on numerical problem solving, examination results indicate that students who have learned in this way often do better than others on quantitative problems and much better on qualitative questions.

C. Certain conceptual difficulties are not overcome by traditional instruction. *Persistent conceptual difficulties must be explicitly addressed by multiple challenges in different contexts.*

Some student difficulties disappear during the normal course of instruction. Others seem to be highly resistant to change. If sufficiently serious, they may preclude meaningful learning, even though performance on quantitative problems may be unaffected. An example of a common difficulty that research has shown to be especially persistent is the apparently intuitive belief that current is "used up" in a circuit.

Deep-seated difficulties cannot be overcome through assertion by the instructor. Active learning is essential for a significant conceptual change to occur. An instructional strategy that we have found effective for obtaining the necessary intellectual commitment from students is to generate a conceptual conflict and to require them to resolve it. A useful first step is to *elicit* a suspected difficulty by contriving a situation in which students are likely to make a related error. Once the difficulty has been exposed and recognized, the instructor must insist that students *confront* and *resolve* the issue. Unlike physicists, students may be willing to tolerate inconsistency.

A single encounter is rarely sufficient to overcome a serious difficulty. Students do not make the same mistakes under all circumstances; the context may be critical. Unless challenged with a variety of situations capable of evoking a given difficulty, students may simply memorize the answer for a particular case. To be able to integrate counter-intuitive ideas into a coherent framework, they need time to *apply* the same concepts and reasoning in different contexts, to *reflect* upon these experiences and to *generalize* from them.

D. Growth in reasoning ability does not usually result from traditional instruction. *Scientific reasoning skills must be expressly cultivated.*

An important factor in the difficulties that students have with certain concepts is an inability to do the qualitative reasoning that may be necessary for applying the concept. It is often impossible to separate difficulties with concepts from difficulties with reasoning. An error may be a symptom of an underlying conceptual or reasoning difficulty, or a combination of both.

A failure to think holistically in dealing with compound systems is one kind of reasoning difficulty that may be hard to disentangle from conceptual confusion. For example, in predicting bulb brightness for the set of three circuits described earlier, students often considered only the order of a bulb in an array.[5] Many claimed that the first bulb in a series network was the brightest. This error is consistent with the misconception that current is "used up" and also with improper use of local sequential reasoning. For interacting systems, such as elements in an electric circuit, it is impossible to predict the behavior of one without taking into account the effect of the others. However, instead of considering the circuit as a whole, many students focused on only one bulb at a time. The conservation of current was an abstraction for which they might be able to write an equation but which they could not apply to a qualitative problem.

Predicting the effect of a change in a circuit requires a more sophisticated level of holistic reasoning. In one task, students were shown a circuit diagram in which a network containing two branches in parallel was connected in series with other bulbs.[5] The students were asked to predict what would happen to the brightness of a bulb in one branch of the parallel network when the other branch was removed. A common response was that the brightness would not change. Often the explanation given was that the bulb was part of a parallel combination. In treating the parallel branches as independent, the students were not recognizing the difference between parallel branches connected across a battery and parallel branches connected elsewhere. Instead of using qualitative reasoning to check that their predictions were consistent with what they knew about current and potential difference, the students relied on a rule that they had incorrectly memorized.

Traditional instruction does not challenge but tends to reinforce a perception of physics as a collection of facts and formulas. Students often do not recognize the critical role of reasoning in physics, nor do they understand what constitutes an explanation. They need practice in solving qualitative problems and in explaining their reasoning. However, they are unlikely to persevere at developing facility in scientific reasoning unless the course structure, including the examinations, emphasizes the importance of this ability.

E. Connections among concepts, formal representations, and the real world are often lacking after traditional instruction. *Students need repeated practice in interpreting physics formalism and relating it to the real world.*

Students are often unable to relate the concepts and formal representations of physics to one another and to the real world. An inability to interpret equations, diagrams and graphs underlies many conceptual and reasoning difficulties.

1. Difficulty with algebraic representations: example from dynamics

Performance on the impulse-momentum and work-energy comparison tasks illustrated the difficulty students frequently have in relating algebraic formalism to physical concepts and to the real world.[1,4] The demonstration creates a simple physical situation in which the relevant theorems can be applied. Nevertheless, few students have been able to connect the mathematical statement of the theorems to the motion.

2. Difficulty with diagrammatic representations: example from optics

In another investigation, students who had studied geometrical optics participated in interviews in which they were shown a demonstration that consisted of an object, a thin converging lens and an inverted real image on a screen.[6] One of the tasks was to predict the effect of covering half of the lens. Most students claimed that half of the image would disappear. The ray diagrams that they drew sometimes reinforced this mistaken intuition. Two of the special rays were often shown as blocked. In interpreting their diagrams, the students indicated that these rays were necessary for forming the image, rather than merely convenient for locating its position.

3. Difficulty with graphical representations: example from kinematics

Student understanding of the graphical representation of motion has been a long-term research interest of our group.[7,8] In one task from this ongoing study, students are shown a ball rolling along a track and given a diagram of the motion with a description similar to the following: The ball moves with steady speed on the level segment of the track, speeds up as it moves down an incline, and then continues at a higher constant speed on the last segment. The students are told that position is measured along the track and are asked to represent the motion in graphs of position, velocity and acceleration versus time. The task has been presented to several hundred students who have studied kinematics. Few students in the standard calculus-based course have produced correct graphs.

We have also examined student difficulties with the reverse process: visualization of a real motion from its graphical representation. The ability to relate actual motions and their graphical representations does not automatically develop with acquisition of simple graphing skills, such as plotting points, reading coordinates and finding slopes. Students need practice in translating both ways: from motion to graphs and from graphs to motion.

F. Teaching by telling is an ineffective mode of instruction for most students. *Students must be intellectually active to develop a functional understanding.*

All the examples of student difficulties discussed above share a common feature: the subject matter involved is not difficult. Many instructors expect university students who have studied the relevant material to be able to answer the types of questions that have been illustrated. Yet, in each instance, we found that a large percentage of students could not do the basic reasoning necessary. On certain types of tasks, the outcome did not vary much from one traditionally taught class to another, nor did it matter when in the course the problems were posed. Enrollment in the associated laboratory course also did not appear to affect the quality of student performance. Moreover, there was no correlation between the success of students and the reputation of the course instructor as a lecturer.

The difficulties that students have in physics are not usually due to failure of the instructor to present the material correctly and clearly. No matter how lucid the lecture, nor how accomplished the lecturer, meaningful learning will not take place unless students are intellectually active. Those who learn successfully from lectures, textbooks and problem-solving do so because they constantly question their own comprehension, confront their difficulties and persist in trying to resolve them. Most students taking introductory physics do not bring this degree of intellectual independence to their study of the subject.

Although the traditional lecture and laboratory format has disadvantages, it may be the only mode possible when the number of students is large. Such instruction, however, need not be a passive learning experience. There are several techniques that instructors of large classes can use to promote active participation by students in the learning process.

III. IMPROVING THE MATCH BETWEEN TEACHING AND LEARNING

The generalizations about learning and teaching presented above have been derived from investigations of student understanding in the context of classical physics. We believe, however, that they have broad applicability and should be taken into account in current efforts to introduce new topics and new technology into the introductory course.

Physicists generally assume that students will find contemporary topics inspiring. It has been our experience, however, that few students are motivated by exposure to material that they do not understand. Instead, the outcome may only confirm a belief that physics is too difficult for most people. There is also great enthusiasm about the potential of the computer for enhancing student learning in physics, especially modern physics. Although there is reason for optimism, our experience suggests a need for caution. Success on a computer task does not necessarily indicate development of a skill that can be transferred to other environments. Even a highly interactive program does not insure that students will make the mental commitment necessary for significant concept development to occur.

Perhaps the most significant contribution that research in physics education can make to the improvement of instruction is to underscore the importance of focusing greater attention on the student. The successful incorporation of contemporary topics or advanced technology into the introductory course is likely to depend as much on *how* the material is taught as on *what* is taught. To insure that the curriculum that is developed will be well matched to the students for whom it is intended, there is a need for research on the learning and teaching of both classical and modern topics, with and without the computer.[8]

Meaningful learning, which connotes the ability to interpret and use knowledge in situations different from those in which it was initially acquired, requires that students be intellectually active. Development of a functional understanding cannot take place unless students themselves go through the reasoning involved in the development and application of concepts. Moreover, to be able to transfer a reasoning skill learned in one context to another, students need multiple opportunities to use that same skill in different contexts. The entire process requires time. Inevitably, this constraint places a limit on both the breadth of material that can be covered and the pace at which instruction can progress. New topics cannot be added without omitting others. Choices must be made. Unless we design instruction to meet the needs and abilities of students, efforts to update the teaching of introductory physics will produce little of either intellectual or motivational value.

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[1] These generalizations were presented in a plenary lecture at the conference, "Teaching Modern Physics: Statistical Physics," Badajoz, Spain, July 18–25, 1992. A more detailed discussion will appear in the conference proceedings.

[2] At a recent conference attended by physicists active in research on learning and teaching, there was general consensus about the validity of the generalizations. The "New Mechanics Conference," which was held at Tufts University, Medford, MA (August 6–8, 1992), was small, but broadly based.

[3] See, for example, A. B. Arons, *A Guide to Introductory Physics Teaching* (Wiley, New York, 1990).

[4] R. A. Lawson and L. C. McDermott, "Student understanding of the work-energy and impulse-momentum theorems," Am. J. Phys. **55**, 811–817 (1987).

[5] L. C. McDermott and P. S. Shaffer, "Research as a guide for curriculum development: an example from introductory electricity, Part I: Investigation of student understanding," Am. J. Phys. **60**, 994–1003 (1992); P. S. Shaffer and L. C. McDermott, "Research as a guide for curriculum development: an example from introductory electricity, Part II: Design of instructional strategies," Am. J. Phys. **60**, 1003–1013 (1992).

[6] F. M. Goldberg and L. C. McDermott, "An investigation of student understanding of the real image formed by a converging lens or concave mirror," Am. J. Phys. **55**, 108–119 (1987).

[7] L. C. McDermott, M. L. Rosenquist, and E. H. van Zee, "Student difficulties in connecting graphs and physics: Examples from kinematics," Am. J. Phys. **55**, 503–513 (1987).

[8] L. C. McDermott, "What we teach and what is learned—Closing the gap," Am. J. Phys. **59**, 301–315 (1991).

WORKING WITH EINSTEIN

Clearly, when I entered Einstein's office, I was quite conscious of the fact that I stood in front of one of the greatest scientists of all time. It would not have been strange if I had been entirely tongue-tied. But this is not what happened. Einstein included me in the conversation that had been going on when I entered his office, and after five to ten minutes, I had forgotten my difficulties and felt entirely at ease.

Valentine Bargmann, in *Some Strangeness in the Proportion*, edited by Harry Woolf (Addison-Wesley, Reading, MA, 1980), p. 480.