PHYSICS IN THE CLASSROOM: HOW CAN WE DO BETTER?

A Guide to Introductory Physics Teaching

Arnold B. Arons
Wiley, New York, 1990. 342 pp. $39.95 hc ISBN 0-471-51341-5

Reviewed by Charles H. Holbrow

This book delighted me. It depressed me. It astonished me. It made me mad. It told me things I have known for a long time. It told me things I can barely believe. The title says the book is a guide to the teaching of introductory physics, but the real guide is Arnold Arons. He lays out for teachers of physics a variety of misconceptions students acquire and labor under as they move through the sequence of topics that make up first-year college physics. He offers detailed suggestions for ways to help students achieve correct understanding. The guide is informed by Arons's more than 40 years of experience at places as different as Stevens Institute of Technology, Amherst College and the University of Washington, and it strongly reflects work from the past decade on cognitive aspects of learning physics.

The generation of understanding is a low-yield process, as anyone knows who has taught physics for more than a few years and has attended to what students actually learn. You find that quite able students who do well on exams and homework problems do not understand basic geometrical and mathematical ideas. Even in the highest level beginning course, there will be students who do not understand the idea of "area." Others cannot follow scaling arguments or rapid manipulation of powers of ten or arguments based on ratios. I knew these things, but among the delights of the book are the surprising things I didn't know. It was news to me that many students, including those who use the word freely, cannot explain the meaning of "per" as it appears in "grams per cubic centimeter," "meters per second" or "per cent." I have since sharply reduced my per-lecture use of "per."

Occasionally the compendium of difficulties borders on the incredible. Reading that many students—especially ones unfamiliar with science—believe there is no gravity in a vacuum and that objects are held on the Earth by air pressure, I was prepared to doubt. Unfortunately, the same day that I read Arons's description of this misconception, a colleague teaching a science course for nonscience majors came to me in amazement with results of an exam in which nearly one-third of the students asserted in one way or another that there is no gravity in a vacuum. Other contributions to the roster of the "amazing but false": North magnetic poles repel positive electric charges; electric charge drips out of electric wall sockets.

But the book is far more than a collection of student difficulties. Arons has some important messages for teachers of physics. Repeatedly he tries to answer the questions: Why is physics so difficult for students, even good ones? Why do students acquire and retain fundamental misconceptions about basic ideas of mass, time, velocity, acceleration, momentum, energy, electric charge, electric currents, electrical and magnetic fields, optical images, waves, interference, superposition and so on? The list covers all of physics, and "the fault, dear Brutus, is not in our stars . . ."

Arons lists the generic faults of teachers of physics. These include far too great a reliance on "verbal inculcation"; the use of teaching materials that rely on abstract reasoning, which are mismatched to student intellectual maturation (in the sense of Piaget); excessive reliance on formal manipulation in homework and examinations; and insufficient demand for student verbalization of their own understanding of the material. Despite the lip service we pay to the ideas of critical thinking and understanding, Arons says that the actual emphasis in exams and homework is on mathematical manipulation, the formula stuffing that we deplore and then test for. Repeatedly he reminds us that what you test for is what you teach, regardless of what you may claim. He acknowledges that many students are content with numerical and algebraic problems that have easily graded answers, but he deplores the "... collusion in which students agree to accept bad teaching provided they are given bad examinations."

How can we do better? Arons calls again and again for a slower pace. Students need time, "time to explore, to test, to manipulate, to talk and argue about meaning and interpretation." He calls for more individual attention to students; he repeatedly asserts the need to engage the student by Socratic questioning. Students must be led to formulate the ideas of physics in their own words. Twenty to thirty minutes of guided conversation, he says, is essential to help a student begin to work his or her way through a conceptual misunderstanding. And always there must be repetition, reinforcement by spiraling back to the ideas many times in slightly different contexts. Arons asks professors of physics to lead students away from "declarative knowledge"—words, verbal definitions, names of things—and toward "operative knowledge"—definition and description in terms of directly comprehendible processes.

To help the teacher of college physics provide this leadership, Arons

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provides concrete examples of homework problems, exam questions and illustrative phenomena that can be used to trigger insight. I have already asked students to discuss the change in pressure that occurs when two immiscible liquids separate out in a narrow necked jar. I am looking forward to using Newton's derivation of centripetal acceleration. I plan to try out the illustration of Faraday's law in a multiply connected region. The book offers physics teachers a number of ideas for immediate use in the classroom.

The book is eye opening and informative, but is its program for improving the teaching of introductory physics feasible? There are two issues here. One is practical. How much time is available for Socratic questioning of students? If it takes 20 to 30 minutes to begin to straighten out one student's misunderstandings of one concept, is this an approach that can be used in a course of 100 students—let alone 1000 students? Students need more time to chew over the ideas of beginning physics, and they need closer guidance as they chew. Where will the time and guidance come from?

The second issue is more basic. How worthwhile is the investment of these resources in generating understanding? I assume "understanding" means the ability to apply correctly the generalizations of physics to specific cases, particularly to ones that have not been met before. Is this kind of comprehension a realistic goal for introductory physics? I doubt that comprehension of a general principle is ever "taught"; I think it occurs in the mind of the learner, often dealing with many different examples of the embodying principle. When I try to remember getting my own misconceptions straightened out, I am struck by how late this occurred in my education. It certainly did not happen in the introductory physics course, which I remember as a kind of interestingly mysterious experience through which I wandered in a daze.

Throughout the book and especially in the concluding two essays, "Achieving Wider Scientific Literacy" and "Critical Thinking," Arons offers the elements of a philosophy of science teaching. Unfortunately they are only elements. His assumptions are not examined closely and the relative weights that he gives them shift. Important issues are not raised. For example, Arons repeatedly argues that "less is more." Less coverage can be transformed into more understanding. He offers some evidence for this, but the issue is one of balance. How much coverage are you trading for how much understanding? His basic assumption is that understanding is good, coverage less good. This assumption needs examination.

As another example, his deprecation of vocabulary as a substitute for understanding is often to the point, but it also shows a parochialism common to physicists. Language is extremely important. Many people, especially nonscience students, make little distinction between the names of things and their reality. It is unrealistic to deplore and ignore this important human trait; it is probably better to exploit it. Arons's stimulating and provocative ideas and opinions are the elements of an educational philosophy; they need to be subjected to philosophical analysis.

The curricular seas of physics have been calm for more than 20 years, but the waters are stirring. Arons has some navigational advice for us—much of it common sense: Learning physics must not be like drinking from a fire hose. Students must come away with some feeling of achievement and satisfaction; the experience cannot be one of unrelieved frustration.

We need to listen to Arons. We do our subject a disservice and fail as teachers if we replace one fire hose with another, or if we substitute exotic taxonomies of quarks and gluons, black holes, band structure or quantum fields for the harder tasks of equipping students with the tools and concepts for independent analysis of the physical world. Arons's book warns against such failings, and it offers practical, useful and stimulating ways to avoid the pitfalls of superficiality. The tacit and explicit assumptions of his views of physics education should stimulate a debate that we need. If you teach physics at any level of the curriculum, read this book.

Discovering: Inventing and Solving Problems at the Frontiers of Scientific Knowledge

Robert S. Root-Bernstein
Harvard U. P., Cambridge, Mass., 1989. 501 pp. $35.00 hc ISBN 0-674-21175-8

In the mid-1960s I served for a time as book review editor for a quarterly educational journal. In the welter of books that poured in, there was one category that seemed to predominate. I still describe it as publishing's infinite sink: Creativity—what it is, who has exhibited it in the past and why, how to nurture it, how not to discourage it, how to develop curricula to promote it, which teaching styles foster it and which discourage it. Many of these books were edited collections of conference papers. Others were collections of reprints of essays and excerpts from monographs, while still others were book-length exegeses exhorting us to be more creative and warning us of the dire consequences to our national vitality if we did not reinforce behaviors among our young that lead to creative adults.

Creativity comes in all shades and all shapes. In truth, we don't know much about what it takes to be a creative person, and we have even less of an idea of how to foster whatever characteristics might be pertinent. Yet the torrent of treatises continues unabated. Still, every once in a while a book on the subject of creativity comes along that forces its way to attention. Such a book is Robert Scott Root-Bernstein's *Discovering.*

Root-Bernstein is a productive biochemist who has made his reputation in science by, among other things, successfully challenging the central dogma in molecular biology by demonstrating that amino-acid pairing allows for direct protein replication. Root-Bernstein has also published many studies on the creative process. And he is well grounded in the history of science: His doctoral dissertation was devoted to the history of the creation of physical chemistry.

Root-Bernstein's proclaimed purpose in this work is to demonstrate how the objective edifice of science is created by human beings who, like all of us, are subject to the ebb and flow of emotions, prejudices and biases. As in some of his other studies, in *Discovery* Root-Bernstein uses the history of science as a heuristic device for exploring "how ... subjective and fallible human minds can nonetheless produce something as powerful as science." But there is a subtext. Root-Bernstein is trying, desperately, to understand the creative process—the creative act. In this work, which he describes as "a colloquium on discovery," he mines history for clues on how to be creative.

While I think such efforts must of needs fail, Root-Bernstein has produced a fascinating Socratic dialogue in which he uses the history of science to reconstruct the conditions surrounding a few key discoveries in chemistry and biochemistry. In the tradition of the dialogues of Galileo, Root-Bernstein has created a modern