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100 Years of Attempts to Transform Physics Education

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As far back as the late 1800s, U.S. physics teachers expressed many of the same ideas about physics education reform that are advocated today. However, several popular reform efforts eventually failed to have wide impact, despite strong and enthusiastic support within the physics education community. Broad-scale implementation of improved instructional models today may be just as elusive as it has been in the past, and for similar reasons.[1] Although excellent instructional models exist and have been available for decades, effective and scalable plans for transforming practice on a national basis have yet to be developed and implemented.[2] Present-day teachers, education researchers, and policy makers can find much to learn from past efforts, both in their successes and their failures. To this end, we present a brief outline of some key ideas in U.S. physics education during the past 130 years. We address three core questions that are prominent in the literature: (a) Why and how should physics be taught? (b) What physics should be taught? (c) To whom should physics be taught? Related issues include the role of the laboratory and attempts to make physics relevant to everyday life. We provide here only a brief summary of the issues and debates found in primary-source literature; an extensive collection of historical resources on physics education is available at https://sites.google.com/site/physicseducationhistory/home.

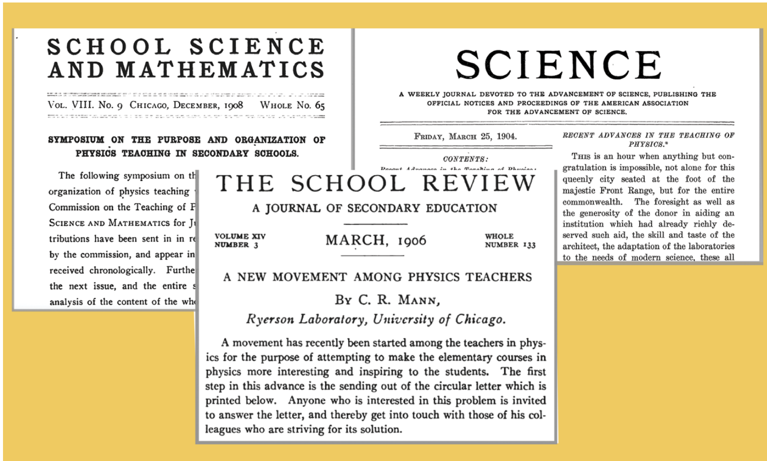

Fig. 1. The journals of the early 1900s were replete with discussions about how to improve the teaching of physics.

Why and how should physics be taught?

When courses in physics (then called "natural philosophy") were introduced as part of the curriculum in the early academies and very first high schools in the early 1800s, the justification was explicitly practical: knowledge of physical phenomena was taught so people could put it to use in their everyday lives. By the early 1880s, however, high school physics teachers would express a multitude of reasons for teaching the subject, including that of training the mind "to habits of accurate observation and of precise and clear reasoning." Hands-on laboratory activities came to be seen as necessary, so that physics students could learn "how to observe, compare, and draw conclusions of themselves," or, in short, "to catch the spirit of inquiry."[3]

Around this time the so-called "inductive method" was widely favored, referring to experimentation that led to student-generated models and explanations for observed phenomena: "[W]e first observe the phenomena sharply and then seek for a cause or for the law according to which the forces act….if the guess is a definite one, definite conclusions (deductions) can be drawn from it which will lead to new observations or experiments….we…continue until one explanation remains that is consistent with all our knowledge and stands all the tests we are able to apply."[3]

Laboratory-based instruction spread rapidly among both high schools and colleges. The well-known "Harvard Descriptive List," a laboratory guide written by E. H. Hall, incorporated many questions, specifically designed to lead physics students to develop models and explanations to account for their observations: "[I]t has been thought best…to put the student, so far as is practicable, into the attitude of an investigator seeking for things unforetold….He should not be told what he is expected to see, but he must usually be told in what direction to look. He should be required to draw inferences from his experiments."[4]

A generation later, these themes were revisited by research physicists such as the University of Chicago's R. A. Millikan, who had a special interest in improving both high school and college physics instruction. Millikan succinctly expressed the views of many physics educators regarding the value of physics, saying that:

> "[T]he material with which it deals is almost wholly available to the student *at first hand*, so that in it he can be taught to observe, and to begin to interpret *for himself* the world in which he lives, instead of merely memorizing text-book facts, and someone else's formulations of so-called laws….The main object of the course in physics is to teach the student to *begin to think for himself,* to begin to construct for himself… an orderly world out of the chaotic jumble of phe-

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nomena which observation presents to him" [emphasis in original].[5]

As these various quotes indicate, early instructional ideals were often envisioned as being based on the inductive method. However, around the turn of the century, an increased emphasis on college preparation along with a growing number of topics to be covered led high school physics to focus excessively on abstract principles and mathematical computations having little physical context, and to a decreasing emphasis on scientific investigation. Cookbook-style laboratory activities took the form of step-by-step procedures, encouraging rote practice and mindless manipulations of laboratory apparatus, rather than inductive reasoning.[6] By 1906, many physics educators had concluded that instruction in physics had gone seriously astray, departing from its original objectives, and they argued strongly for a return to those objectives. For example, physicist C. R. Mann advocated laboratory-based investigations that would engage students' intuitive thinking, promote inductive reasoning, and help students experience the "spirit of science," which he defined as a belief that "the world is a harmonious and well-coordinated organism and that it is possible…to find harmony and coordination."[7] The "New Movement Among Physics Teachers" attempted to gather support for reforms aimed at goals such as this. Later, the increasingly popular "project method" saw students engaged in practical investigations of topics that might arise from their everyday lives and experiences.[8]

By the 1930s, a strong current of practicality had overtaken the teaching of high school physics and it reoriented instructional priorities. In this post-war period, university-based physicists had largely turned their focus away from education and toward expanded research opportunities, leaving faculty from education schools to drive the conversation about K-12 science teaching; thus, high school physics curriculum and instruction moved in a markedly "applied" direction. Physics was to be taught not primarily to help students "catch the spirit of inquiry," or even "to begin to think for [one]self" (although similar goals were still cited), but instead to inform and assist students' interactions with the products of science such as electrical lighting and power systems, heating and refrigeration, and machinery and transportation. High school physics textbooks became increasingly dominated by descriptions and illustrations of technological devices. Discussions of physics principles were viewed as useful adjuncts for improving students' understanding of technology that they experienced in everyday life, but thorough understanding of those principles was *not* a primary goal of instruction.[9] This viewpoint was largely unchallenged until the resurgence of physicists' involvement in high school instruction that occurred after World War II, beginning in the late 1950s.

The physicists' post-war reengagement with physics education also marked a renewed emphasis on the goals originally expressed during the 1880s and reiterated in the early 1900s, that is (as enunciated by the Physical Science Study Committee [PSSC] in 1960): high school physics instruction should lead "to an understanding of how we find simplicity beneath the tremendous complexity of our surroundings. Students acquire an insight into the scientific process, not merely a catalogue of scientific and technological facts."[10] More broadly, the Harvard Project Physics course set out explicitly to "show the science of physics in its proper light as a broadly based intellectual activity that has firm historical roots and that profoundly influences our whole culture." Project Physics also had another, perhaps even more ambitious aim of attracting a larger number of high school students to the study of introductory physics.[11]

In the 1970s and 1980s, education researchers in university physics departments took for granted the value of teaching physics; however, their Physics Education Research (PER) revealed severe shortcomings in students' understanding resulting from traditional instructional methods. This new generation of physics educators provided evidence suggesting a need for instruction that engages students in a specific type of hands-on lab and problem-solving activity, using curricular materials developed through research into students' learning. They stressed the importance of building on students' everyday ideas and developing qualitative understandings. Physics Education Research workers also consciously refined the inductive, questioning-based instructional techniques previously used in the 1880s and 1960s, now honed through rigorous research and iterative cycles of testing and revision to sharpen pedagogical materials for maximum effectiveness.[12] In this, they were building consciously and explicitly upon the active-learning instructional methods that had been incorporated in the physics education reforms of the 1950s and 1960s.

Since 1980, hundreds of articles and reports have justified the study of physics (and other sciences, as well as engineering and math) by emphasizing the need to develop knowledge and skills for surviving in a technology-focused economy.[13] While development of technical skills and knowledge is unquestionably a very important reason for studying physics, an exclusive focus on this objective loses sight of other goals, arguably no less urgent, that were promoted a century ago by physics educators such as Hall, Millikan, and Mann. For example, these authors emphasized that the study of physics is uniquely suited to enable students to begin to interpret for themselves the world in which they live. Developing classroom practices that promote this goal remains today the great challenge it has always been.

What physics should be taught?

The early texts in natural philosophy were largely qualitative, providing detailed discussions and practical information on a wide variety of useful topics including mechanics, electricity and magnetism, fluid statics and dynamics, meteorology, acoustics, and optics. Many dozens of technological devices were described and illustrated, including pumps, batteries, telescopes and microscopes, mechanical devices, and musical instruments. After 1880 and continuing for the next 30 years, it became increasingly common to include experiments intended for students to carry out themselves (often in separate laboratory manuals). There was a much greater focus on precise measurement and data analysis and, increasingly, on mathematical formalism and problem solving. In reaction against this trend, the "New Movement" started in 1906 by high school and college physics teachers advocated a more tightly focused syllabus with fewer experiments, a stronger qualitative orientation, and extensive use of practical "problems" that emphasized laboratory investigations of phenomena experienced in everyday life.[14]

Another major new trend beginning around 1910 was the introduction of the high school general science course by education faculty, deliberately designed to appeal especially to students who were supposedly not interested in or capable of focused study of "special" sciences such as physics and chemistry.[15] The general science course attempted rapid coverage of a wide variety of topics in physics, chemistry, astronomy, biology, meteorology, and Earth science. In contrast, physics educators persisted in advocating for the physics course: C. R. Mann emphasized the potential of physics to arouse within students the "scientific spirit," while R. A. Millikan asserted that physics was "perhaps better adapted than any science, to arouse the interest and to appeal to the understanding of the child of from twelve to fourteen years of age."[16] This outlook was notably absent in the writings of proponents of general science. Moreover, the general science "philosophy" began to permeate the physics courses themselves. Physics curricula increasingly emphasized everyday technology as a means for "connecting to students' daily lives." Textbooks focused on the uses and applications of physics in the form of a vast array of electrical and mechanical devices. Discussions of fundamental physical principles and laws were often brief, lacking much evidence or reasoning details.

Physics curriculum reforms of the 1950s and 1960s targeted all levels of instruction, elementary through high school. The high school-level curricular materials, most notably PSSC and Project Physics, strongly emphasized reasoning from evidence and incorporated laboratory-based investigations; they focused on fundamental principles instead of technological applications in "everyday life," and included some discussion of topics in modern physics. They also provided extensive historical and cultural perspectives on physics (particularly in Project Physics). New college-level texts dropped many "practical" topics and instead emphasized fundamental unifying principles with substantially increased focus on modern physics.

Beginning in the 1980s, "conceptual" physics courses that emphasized qualitative descriptions and minimized use of mathematics contributed to the rise in high school enrollments. At the same time, an unprecedented proliferation of PER groups in colleges and universities yielded dramatic insights into physics students' reasoning processes. This led to recognizing the importance of taking students' specific physics ideas into account when designing instructional materials, as well as placing a stronger emphasis both on qualitative analysis and on students' active engagement in problem solving during class time. As the PER community grew during the 1990s, a wide variety of research-based active-learning curricular materials was produced and disseminated, primarily targeted at the college level but occasionally reaching into the middle schools and high schools through such projects as Modeling Instruction and Tools for Scientific Thinking.[17] The most widely used high school texts attempted to balance qualitative and quantitative problem solving and assessment, but still included an enormous range of topics for what was and has remained a one-year course.[18]

Teach physics to whom?

Natural philosophy was, as a rule, a required course for students in most high school curricula before 1900,[19] although many left school before reaching the upper grades in which it was usually offered. (And, many who took it dropped out before graduating). Before 1900, less than a third of all students who began high school ended up graduating.[20] Since girls tended to stay in school longer than boys, girls substantially outnumbered boys in physics classes: over 58% of physics students in 1890 were girls,[21] even though nearly all boys and girls who had the opportunity to take a physics class did so.[22] (In fact, they were usually *required* to do so.) Although nearly all high school graduates before 1900 had taken a physics course, they comprised less than 3% of the age-17 population in 1880.[23]

By 1910, even after 30 years of dramatic increases in enrollment, high school graduates still constituted less than 9% of their age cohort. By this time, most high schools had stopped requiring physics; even so, about three-quarters of graduates still took a physics course. However, the gradual decline in physics enrollment (decline in *proportion*, since absolute numbers were increasing) was cause for alarm among science educators; as early as 1901 (when the decline was barely noticeable), this decline was claimed to be evidence that the physics course was uninteresting and distasteful to most high school students,[24] a claim unsupported by any other significant evidence and one strongly denied by physics educators such as Millikan.

In fact, until around 1910, nearly all boys continued to take physics when it was available to them. However, between 1890 and 1910, the comparable proportion of girls taking physics dropped significantly (from nearly 100% to around 75%), even though girls still marginally outnumbered boys in physics classes.[25] Researchers have suggested that many girls at this time had begun to turn away from science classes so that they could instead enroll in some of the new "practical" offerings available such as home economics, business, typing, and stenography.[26] Girls' enrollments in those courses rose rapidly, far outstripping the boys, at the same time that boys were accounting for a steadily increasing proportion of physics enrollments. By the 1920s, as more boys continued to stay in school long enough to graduate, they had come to clearly outnumber girls in physics: in 1922, 59% of physics students were boys.[27] However, proportions of both boys and girls taking physics continued to drop, to around 70% of boys in 1922 (down from nearly 100% in 1910) and 40% of girls (down from around 75% in 1910). This was not necessarily due to some failing of the physics course, although that was often suggested. Rather, the rapid rise of the elective system and an enormous increase in the number of elective subjects available—including business and commercial courses, as well as popular new courses in biology and general science—tended to push down the proportion of students enrolled in many traditional academic subjects such as mathematics, languages, physiology, and physics.

Even after numerous cycles of reform aimed at making the physics course more attractive to students and interesting to girls,[28] complaints that it was "stale," "nonfunctional," and overly focused on college preparation would continue unabated into the 1940s and 1950s. By the 1950s, only 20-30% of physics students were girls.[29] At some point, that proportion began to climb back towards its previous levels, reaching 40% by the late 1980s and nearly 50% by the late 1990s; that is roughly where it stands today.[30] Despite all efforts to make the course more "interesting," more "relevant to everyday life," and more "psychologically" attuned to the student audience, the proportion of high school graduates taking physics declined, virtually continuously, between the 1920s and mid-1980s, by which time it had fallen below 20%.[31] In most schools, there was only a single, one-year physics course available to students, and efforts to reform it clashed with the need for it to serve diverse interests such as college preparation, teaching of laboratory skills, and communication of factual information considered to be important.

As is clearly expressed in many dozens of articles written by physics educators during the past 130 years, high school and college physics teachers have long believed that physics has, potentially, much to offer the broader student population, and that therefore a proper course design should be able to attract a larger proportion of those students; for example, this was one of the stated goals of Project Physics in the 1970s. By contrast, some of the other reform efforts that took place in the post-*Sputnik* era aimed specifically at those students who were *already* taking physics courses; their goal was to improve those students' experiences and lead them to a better understanding both of physics principles, and of the nature and social importance of fundamental research in physical science. The principal example of this type of course was the one created by the Physical Science Study Committee.

It is yet another irony in the history of physics education that when the situation actually did turn around, it was not the product of any systematic, organized effort. With increasing state science requirements accompanied by the rise of "conceptual" physics courses and textbooks in the 1980s (supplementing the standard college-preparatory course), together with significantly increased interest in Advanced Placement courses, the long-sought-for reversal began. The proportion of high school graduates taking physics began to rise during the 1980s, a process that has continued without a break until the present day; it has now reached nearly 40%, with no obvious stopping point on the horizon.[31] In the end, the development and wider dissemination of diverse physics course offerings seems to have been at least one crucial key to broadening the population exposed to the study of physics.

Since the early 1900s, physics educators have worked to make physics attractive and relevant to diverse populations of students. With an increasing diversity of physics offerings in the past 30 years, these efforts may finally have begun to pay off.

Conclusion

The historical literature in physics education reveals a substantial consensus among physicists and high school physics teachers on desired instructional methods and outcomes. Actually realizing these methods and outcomes in real classrooms has presented a major challenge for over 130 years, a challenge that continues today. We hope that the current article provides the reader with ideas that are useful for guiding decisions about where to place efforts in educational change.

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