A brief history of physics education in the United States

David E. Meltzer[a)]
Mary Lou Fulton Teachers College, Arizona State University, Mesa, Arizona 85212

Valerie K. Otero[b)]
School of Education, University of Colorado, Boulder, Colorado 80309

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In order to provide insight into current physics teaching practices and recommended reforms, we outline the history of physics education in the United States—and the accompanying pedagogical issues and debates—over the period 1860–2014. We identify key events, personalities, and issues for each of ten separate time periods, comparing and contrasting the outlooks and viewpoints of the different eras. This discussion should help physics educators to (1) become aware of previous research in physics education and of the major efforts to transform physics instruction that have taken place in the U.S., (2) place the national reform movements of today, as well as current physics education research, in the context of past efforts, and (3) evaluate the effectiveness of various education transformation efforts of the past, so as better to determine what reform methods might have the greatest chances of success in the future.
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I. INTRODUCTION

The teaching and learning of physics has long been a focus for the U.S. physics community, and physics education in the U.S. has undergone many significant changes during the past 200 years. Virtually all academic physicists, whatever their age, have been exposed to—and encouraged to participate in—efforts to reform and improve the way physics is taught, either at the K-12 or college level. Recently, there have been increased calls for university physics faculty and high school physics teachers to transform their courses, for example, by more directly incorporating scientific practices and by aligning instruction more closely with findings from research on student learning. Systematic physics education research (PER) has provided evidence supporting the use of various specific instructional strategies.[1] However, there has been little attention given to the history of physics education and to how the many reform efforts and often stormy debates of the past have played out. Few have asked, for example, how today's pedagogical initiatives differ—or don't differ—from those of the past, or what exactly has changed—or not changed—as a result of previous reform efforts. An obvious question to ask is "What must be done to avoid the shortcomings of previous efforts at reform?" Although we are not able to answer that question here, we provide a basis for initiating the discussion.

A careful examination of the U.S. physics education literature dating back as early as the 1880s reveals that there are many similarities between the early writings about educational transformation and the discussions that are taking place today.[2] In some cases, it is difficult to determine whether a quotation came from an article by a physics instructor published in 1912 or from a report by a national commission issued in 2012. It can be surprising to realize that calls for physics education reform have remained relatively consistent in many ways during the past 100 years or more. Another recurring pattern is that writings from each time period rarely refer to the national reports or other published documents or research from earlier periods. For example, for the past 130 years physics education reformers have been calling for increased engagement by students with the practice of scientific induction (called "inquiry" or "scientific practices" in more recent times). However, it seems that this theme was continuously rediscovered in each era as the intense and passionate debates of previous times were largely forgotten or overlooked.

In Sec. II, we have organized the history of U.S. physics education into ten thematic segments, or chronological "periods." We summarize the key literature from each period and discuss major events, personalities, and issues of the day. In Secs. II A–II G, our focus is primarily on physics in the high schools and on college preparation requirements, since that arena was the center of most broad-based pedagogical debates and reform efforts by physicists and physics educators until the late 1960s. In Secs. II H–II J our focus moves to the colleges and universities. In Sec. III, we provide a summary, and offer a number of (unanswered) questions that could be productively addressed by physics educators and physics education researchers of the present day.

II. HISTORICAL OUTLINE OF U.S. PHYSICS EDUCATION

A. Origins of physics education in the U.S., 1860–1884

This early period—similar to several that immediately follow it—is transitional in the sense that physics teaching was undergoing a rapid and wide-ranging transformation. Physics (known originally as "natural philosophy") had been taught at the secondary level in academies and high schools since the early 1800s, its inclusion in the curriculum being justified in large part by its practical utility and relevance to everyday life. However, only during this period did physics and other sciences begin to gain a firm foothold in college curricula after long resistance by proponents of "classical" education. From then on, the evolving relationship between high school and college physics instruction would become a major theme of U.S. physics education.[3]

At the beginning of this period, instruction was largely tied to textbooks and was primarily through lecture, "recitation" (which meant literal recitation by students of textbook readings), and occasional demonstrations by the instructor. High school textbooks focused on providing factual information and on explanations of everyday phenomena. Although the use of mathematics in these books was limited, it became increasingly common to find quantitative practice problems at the ends of chapters, in contrast to the overwhelmingly qualitative emphasis of earlier textbooks. Popular high school textbooks of the era included those by Quackenbos[4] and Steele.[5]

Although nearly all high school students who reached the 12th grade took physics, this group represented less than 5% of their age cohort in the population (see Fig. 1).[6] Until the end of this period, laboratory work by students was rare, both in high schools and colleges; around 1880, laboratory instruction began gaining favor. Student laboratory work came to be seen as necessary to achieve physics instructors' aims, which were explicitly stated to be both understanding of physical principles and improvement in ability to observe and reason from observations. The "inductive method" was widely favored, at least in principle, referring to the execution and analysis of experiments preceding any explicit statement of general principles underlying those experiments. Textbooks to support this method appeared only toward the end of the period, and it is unclear how widely the inductive methods were actually employed. Even by the end of this period, only a handful of secondary schools had actually implemented full-year laboratory-based courses; an extensive national survey carried out in 1878 by F. W. Clarke revealed only four schools that reporting having reached this level, along with about 30 colleges and universities.[7] By contrast, the two decades to follow would see an explosion in the widespread implementation of laboratory instruction.

In 1884, University of Michigan physics professor C. K. Wead published the results of yet another extensive national survey, this one on the purpose and methods of teaching high school physics.[8] The survey was circulated among faculty at normal schools, secondary schools, colleges, and universities throughout the U.S. Responses largely favored the inductive method; arguments were made in support of developing observational skills, drawing conclusions from data, and "catching the spirit of inquiry" (Wead, p. 37), a theme that would persist for many years to come. Respondents were generally opposed to the "unscientific habit of memorizing," which many attributed to the overuse of textbooks. Wead's report makes clear that the difficulty lay in how to actually implement teaching through the inductive method on a broad scale in the high schools; he frequently called attention to Gage's textbook,[9] which was at the time unique in providing support for such methods.

B. The move toward laboratory science instruction, 1885–1902

Throughout the late 1800s physics educators increasingly argued for the use of student laboratory experiments and inductive methods of instruction in the high school physics classroom. (Physics laboratory instruction had been pioneered in college classrooms by MIT beginning in 1869.) However, respondents to Wead's survey disagreed to some extent about whether high school physics should be required for college admission, and on whether the "prevailing character" of the work should be for "information or for discipline," or for both. Though high school education was initially intended to serve students who were not bound for college, many students who enrolled in college were coming from the high schools. Thus, university administrators and faculty felt a need to establish clear college admission standards. The president of Harvard charged physics instructor (later professor) E. H. Hall with the task of developing a list of physics experiments that would be required for admission to Harvard. In 1886, Hall published the first of several versions of this list to guide high school physics teachers in preparing students for college. This "Harvard Descriptive List" had a substantial influence on the discourse and policies of physics education over the next several years,[10] and its influence was amplified by the textbook written by Hall and Bergen that incorporated the entirety of the Descriptive List.[11]

Concurrent with ongoing disagreements about the purpose of high school science, the nation was dealing with very large enrollment increases and increasing numbers of course and curriculum offerings. The National Educational Association (NEA) appointed a "Committee of Ten" to make recommendations for addressing the rapidly changing high school environment. The report of the Committee of Ten

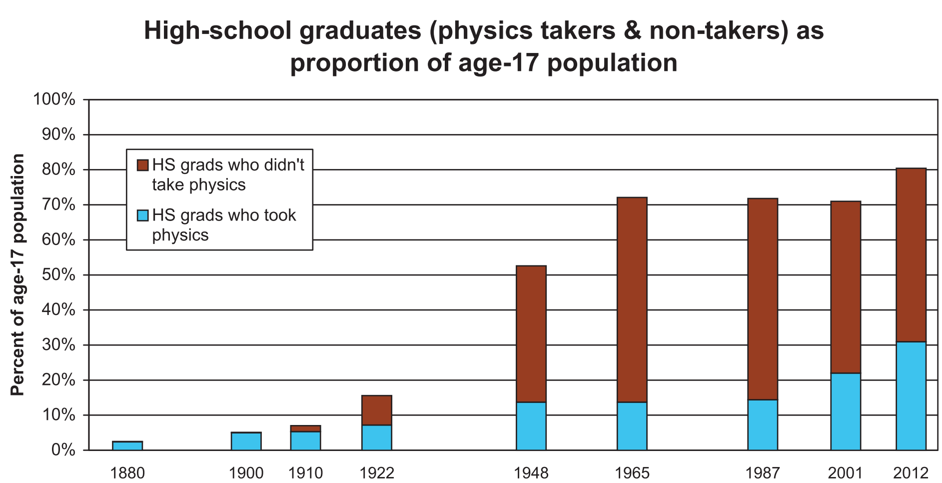

Fig. 1. High school graduates (physics-takers and non-physics-takers) as a proportion of the age-17 population, selected years; includes graduates of both public and private schools, but private school enrollment for some years is estimated. Some figures are interpolated. Sources for enrollment and percentage of graduates include those in Ref. 89; additional population data are in Ref. 90. Source for physics takers, 1948 and after: Ref. 62, p. 1. Sources for graduates and physics takers before 1948 are in Ref. 91. Percentage of physics-taking graduates for 1910 and 1922 is estimated by assuming that physics enrollment was evenly split between grades 11 and 12; see, e.g., Ref. 92.

recommended that both college-bound and non-college-bound students should be taught the same way and that high school physics should be heavily laboratory based, incorporating at least 200 h of study.[12] The Committee's recommendations received further endorsement in the 1899 report of the Committee on College Entrance Requirements, whose physics committee was chaired by Hall.[13]

The Committee of Ten's report stated explicitly that the *main* function of secondary schools was to prepare students "for the duties of life," and not to prepare them for college (Ref. 12, p. 51). However, it turned out that a majority of its recommendations were closely aligned with many of the requirements for college entrance. Another strong connection between college requirements and the nature of high school physics instruction came at the turn of the century, when the newly formed College Entrance Examination Board was charged with writing entrance exams to aid colleges in selecting candidates for admission. The various entrance requirements and standards strongly influenced high school teaching, and set the stage for much further debate regarding the purpose and methods of high school physics teaching. The next period would see a "New Movement" in physics education arising in response to these new challenges.

C. "New Movement" among physics teachers, 1903–1910

By the early 1900s, there was broad recognition that high school physics instruction was not living up to the vision laid out earlier by physicists and science educators. Instead of instruction centered in the laboratory and relying on the inductive method, courses became increasingly formal, textbooks became increasingly mathematical,[14] and laboratory instruction became increasingly "cookbook" in nature through emphasis on highly prescribed step-by-step procedures carried out by rote.[15] During this period, the need to improve the overall quality of instruction was a central topic of journal articles on physics education. One particularly well-organized reform effort came to be known as the "New Movement Among Physics Teachers."

Following the report of the Committee on College Entrance Requirements, journals and conferences saw increasing complaints from physics educators who blamed overly rigid college admission requirements, among other things, for the poor quality of high school physics instruction. Failure rates on the physics exam set by the College Entrance Examination Board were high and rising; in 1907, 61% of examinees failed to achieve a grade of 60% or better, the level often adopted as the "passing" standard.[16] Many argued that this was because college entrance requirements led to overcrowding of high school curricula with sophisticated mathematics and overly precise (but mindlessly executed) laboratory measurements, resulting in rote memorization rather than deep understanding of physics concepts and experimental methods. It was argued that physics experiments and textbook problems had become so quantitative and were presented in such abstract contexts that it was difficult to teach physics as relevant, interesting, or connected to students' everyday lives. Physics teachers reported that drilling of decontextualized information led to students ending up with misconceptions, a distaste for physics, and lack of understanding of the true spirit of science.[17]

The self-titled "New Movement Among Physics Teachers" began in 1906 as an effort to "make the elementary courses in physics more interesting and inspiring to the students"; to this end a committee, consisting of two high school teachers and a physics professor, was appointed by the Central Association of Science and Mathematics Teachers. The committee's initial step was to send out a survey to high school physics teachers around the nation, publishing the survey in the two leading science education journals.[18] The survey solicited opinions on which experiments should be regarded as "essential" for the first year's work in physics, and also asked teachers' opinions on what was "most needed to make physics more interesting, stimulating, and inspiring to the students, and more useful as an educative factor." Extensive results of this and several follow-up surveys were published in both leading journals over a two-year period.

In part due to the diversity of the opinions disclosed by the surveys, a journal-based symposium was initiated and published in the form of a sequence of articles in the journal *School Science and Mathematics* from December 1908 through March 1909. A wide variety of education experts were invited to discuss the "purpose and organization of physics teaching in secondary schools." The 13 participants included educational reformers such as John Dewey and university physicists such as Robert Millikan and Albert Michelson, along with science education professors from universities, teachers' colleges, and normal schools; also included were high school physics teachers and principals, educational psychologists, and a college president.[19]

D. "Project method" and early beginnings of PER, 1911–1914

During this period, several lines of thought were culminating while some newer ones were gaining a foothold. The New Movement had fully matured—in fact, henceforth it would no longer be referenced explicitly in contemporary writings. There was widespread awareness and considerable acceptance among physics teachers of a commitment, at least in principle, to incorporate more "practical," "interesting," and "meaningful" laboratory and classroom experiences into their courses. This period saw the early beginnings of the so-called "project method" in which students were to be engaged in lengthy investigations—sometimes lasting days or weeks—that focused on practical questions, of interest to students, that might arise from (or be connected to) their everyday life experiences.[20] At the same time, spurred on by educational researchers such as Thorndike, physics educators were becoming sensitive to the need to apply rigorous investigative techniques to the improvement of physics teaching; a handful of tentative research investigations were published in the journals during this time.[21]

The other major new trend during this period was the introduction in the high school curriculum of a "General Science" course. This was 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.[22] Of all the events of this period, the creation of General Science is arguably the one with the greatest surviving influence—it remains in existence to this day in the form of the physical science course, typically taught in the 9th grade, and often required of all high school students. The major proponents of General Science were science education faculty in the normal schools and teachers' colleges, many of whom expressed deep skepticism regarding both the desirability and effectiveness of teaching "special" sciences in the high school. By contrast, some physics educators—notably Millikan—believed that General Science would serve merely to draw capable students away from studying physics and the other sciences, wasting their time with superficial and ultimately ineffective survey courses rather than deep, focused, and meaningful study.[23]

This period saw the publication of the greatest synthesis in U.S. physics education of the first half of the 20th century, C. R. Mann's *The Teaching of Physics for Purposes of General Education*.[3] In this influential and widely cited work, Mann summarized the entire historical development of U.S. physics education, and discussed the motivations and goals—both philosophical and practical—of the New Movement that he had led. To address the quandaries facing contemporary physics educators, Mann recommended embracing a form of the project method, supported by specially designed textbooks such as the one he and G. R. Twiss had recently brought up to date in a second edition.[24] Mann believed that the physics teacher's ultimate objective must be to engage students in activities that could awaken the "scientific spirit": "The essence of the scientific spirit is an emotional state, an attitude toward life and nature, a great instinctive and intuitive faith. It is because scientists believe in their hearts that the world is a harmonious and well-coordinated organism, and that it is possible for them to find harmony and coordination, if only they work hard enough and honestly enough and patiently enough, that they achieve their truly great results. It is this faith inside them that inspires them to toil on year after year on one problem."[25] Appreciation of this outlook on science education was notably absent in the writings of those science education faculty who were proponents of the General Science course.

E. Reorganization of secondary curriculum, 1915–1922

During this period, explosive growth in high school enrollment was accompanied by decreasing proportions of students taking physics and other sciences, along with disturbingly low scores on the college entrance exams (see Fig. 1 and Table I). The upshot was to reignite debates about restructuring and revising the entire secondary science curriculum.

In 1918, NEA's Commission on the Reorganization of Secondary Education (CRSE) published the so-called "Cardinal Principles" of secondary education, which focused on preparing students for "everyday life."[26] The Commission's Science Committee published their own report in 1920, including a separate section by the physics subcommittee; the subcommittee's chair was G. R. Twiss of Ohio State University, Mann's collaborator, who had co-authored their joint physics textbook a decade earlier.[27] Although the physics subcommittee's report acknowledged the need for connecting physics to students' everyday lives, it expressed firm commitment to experimental methods, emphasizing genuine laboratory-based investigations that could lead to the induction of physics principles and the nurturing of what Mann had called the "scientific spirit." It was in this context that the report cited the project method (Ref. 27, p. 52).

Table I. Percentages of high school graduates (both public and private schools) who had taken a physics course, for various years. For sources see Fig. 1 caption. Note: Before 1920, many students who took physics in the 10th or 11th grade did not graduate; before 1900, 40% or more of those who took physics did not graduate from high school.

1880	1900	1910	1922	1948	1965	1987	2001	2012
~100%	~100%	76%	47%	26%[a]	19%[a]	20%	31%	39%

[a]Public schools only.

Science education faculty in normal schools and teachers' colleges (whose primary responsibility was the education of future teachers) were generally in favor of the "science for everyday life" approach and they played an increasingly prominent role in the debates over the secondary science curriculum. The science educators, too, used the term "project method" to represent a key component of their activities, although their goals and vision of the project method differed significantly from that of the physicists. They viewed the inductive process primarily as promoting an understanding of how human-created technology worked, rather than as exemplifying a general attitude toward life that (as Mann said) "the world is a harmonious and well-coordinated organism, and that it is possible for [scientists] to find harmony and coordination, if only they work hard enough and honestly enough and patiently enough." Some sense of the science educators' thinking is captured by quotes such as: "Since facts are the groundwork of science, any science study must be informational, and a very large amount of information is defensible in a first-year course,"[28] "science is a cold, impartial presentation of fact. It fails to stir the emotions, to stimulate the will,"[29] and "the search for unique objectives for science is foredoomed to failure, since science shares with other subjects in all the functions of education."[30]

Science teacher educators valued high school science primarily for the technical preparation of citizens in an increasingly industrialized society. Their focus was not so much on the concepts and principles of science but, instead, on developing familiarity with technical processes and objects found in everyday life through projects such as "how the steam engine works," "why gasoline is dangerous," and "distillation of petroleum." For them, development of scientific habits of thought was a subsidiary goal. (A very similar orientation would arise in the 1970s among science education proponents of "science, technology, and society.") There is little evidence that they understood the broader goals that so strongly motivated the leading physics educators.

The perspective of the science educators stood in pointed contrast to the views of Mann, Twiss, and Millikan, among others, and arose from sharp differences regarding the ultimate purpose and value of science education. As illustrated by Mann's statement quoted above, the physics educators' focus was on guiding students to adopt an attitude toward life: seeking harmony and coordination in the universe by engaging in authentic, laboratory-based experimental investigations employing concepts and methods of physics. Physics educators such as Twiss argued that the purpose and value of school science was to create a scientifically literate citizenry, capable of understanding and valuing both the method and the spirit of scientific research. The support of a public both knowledgeable and appreciative of science was seen as vital to sustaining national strength in scientific innovation while making appropriate democratic decisions for the nation's economic and intellectual well being.[31] The physicists' method for achieving these goals was to create high school classroom contexts that could inspire students with the spirit of science, providing them with opportunities for immersion in the transformative experience of scientific induction. (Nearly identical reasoning would motivate a new generation of physics educators in the 1950s and 1960s to make another attempt to establish this type of classroom environment; see Sec. II G below.)

The term "project method" captured the distinct views of both physicists and science teacher educators, and therefore caught on despite the very different meanings attributed to it by these two groups. However, by 1922 the physicists' voice had largely vanished from the scene due to increased demands and opportunities in research.[32] This allowed science teacher educators to take hold of the high school science curriculum and to consolidate a space for General Science, which increasingly became synonymous with science for everyday life.

F. Dominance by educationists, 1923–1947

In contrast to earlier periods, this period saw a sharp division between physics educators at the high school and college levels, with each group pursuing separate and distinct objectives. University-based physicists were now almost absent from the high school scene, due in part to greatly increased demands and rewards associated with both privately funded and government-funded research. Instead of physics professors, it was now primarily faculty from education schools who drove the conversation about K-12 science education and debated the merits of various curricular and instructional reforms. High school curricula were characterized by the "physics in everyday life" emphasis that had been presaged by the New Movement, but institutionalized through the "Cardinal Principles" of 1918 and particularly by the 1920 CRSE report on Reorganization of Science in Secondary Schools. Textbooks, new and revised curricula, and journal articles predominantly focused on ways to teach students about the uses and applications of physics in the form of electrical lighting systems, mechanical and electrical machinery and power systems, heating and refrigeration systems, and so forth.

The surging interest in education research among education faculty (from teachers' colleges and schools of education), and on basing educational decisions—at least in principle—on that research, was now yielding a number of Masters and Ph.D. dissertations and journal articles in which various high school physics instructional methods and curricular materials were put to the test. (During this time, there was almost no education research related to the teaching of college physics.) The research was often carefully done, even by modern standards, but the pedagogical goals as embodied in the assessment materials and diagnostic tests were strongly focused on factual recall related to applications-oriented topics. A few exceptional investigations that included a conceptual and qualitative focus, analogous to many modern approaches, stood out in contrast.[33] However, these few seem to have had little impact on overall trends in physics teaching.

A different course of events was taking place among university physicists. Education-oriented physicists, represented through committees formed by the American Physical Society, turned their interests toward analyzing and reforming university-based physics education so that it would better fit the needs and interests of various constituencies such as agricultural, medical, and engineering students.[34] Finding little resonance among the larger physics community, these education-oriented physicists collaborated to create the American Association of Physics Teachers (AAPT) on the last day of 1930; the American Physics Teacher (later to become the American Journal of Physics) was first published in 1933.[35]

Another major theme of this period was a substantially increased interest in physics teacher education, an interest that extended to the universities. The need for improved and expanded education of science teachers was felt in many science disciplines, as well as in mathematics, and led to unprecedented levels of cooperation through the formation of various joint committees and the issuance of reports by these committees.[36] In the early part of this period, even education faculty were strong advocates for substantially increasing the subject-matter competence of high school science teachers, and of instituting appropriate standards and regulations aimed at ensuring such an outcome. The actual record of accomplishment of these various well-intentioned efforts was very limited. In retrospect, this outcome was attributable to the enormous practical, logistical, and social challenges to changing either the teacher preparation system or the science education system as a whole.

G. Re-engagement by physicists and rise of curriculum reform, 1948–1966

The events of this period were shaped both by experiences of the war years and by post-war concerns regarding the role of science and scientists in American society. In the short term, Cold War worries about technological security, combined with war-induced shortages of technical personnel, catalyzed significant re-allocation of resources into scientific and technical education. The net effect was to initiate processes that would in many respects transform U.S. physics education and science education in general, establishing a foundation for further developments that continue to the present day.

The central role played by physicists during the war dramatically increased the importance put on supporting and training physicists, as well as other scientists and technically skilled personnel, by government, industry, and the population at large. A key outcome of this transformed social outlook was the creation of the National Science Foundation (NSF) in 1950, along with various science advisory committees that had access to and influence on the highest levels of government. Although a central federal funding mechanism for scientific research had been discussed and debated for at least 65 years, it wasn't until the Cold War that political resistance to this idea was finally overcome.[37] However, in the short term, the single most transformative event of this period was the launch of the Sputnik satellite by the Soviet Union in 1957. The shock and concern that this launch generated among the U.S. public and policymakers was so enormous that federal funding for mathematics and science education increased by an order of magnitude in less than three years.[38] Several recently started projects that had already engaged university-based physicists in efforts to improve high school physics were given powerful and unprecedented impetus by the sudden outpouring of Congressional support.

The most direct outcomes of these events were (1) a very rapid expansion in the number of physics (and other science and math) teachers receiving in-service training in summer and academic-year "institutes" funded through NSF and private corporations, and (2) a vast proliferation of federally funded K-12 science curriculum development projects aimed at transforming classroom instruction on a national basis. The instructional materials and methods of many of the new curriculum projects strongly emphasized in-depth conceptual reasoning, investigation-oriented student laboratory activities, reasoning from evidence, and a focus on relatively few fundamental, unifying principles instead of a myriad of technical applications. The most significant of these projects from the standpoint of physics were the Physical Science Study Committee (PSSC), initiated during 1956–1960,[39] and—about a decade later—Project Physics.[40]

University-based physicists, including some of great renown, were heavily involved in the leading curriculum development projects as well as in most of the in-service training institutes. Both the teacher training and the curriculum projects had a strong physics content focus. Although cultural and historical perspectives were integrated into the curricula to varying degrees, little attention was paid to technological devices and other "everyday" applications. By contrast, and during this same period, high school science teachers and science teacher educators pressed on with their efforts to make physics more "relevant" to everyday life by stressing technology and social applications. Their textbooks focused increasingly on illustrations of technological devices, often relegating treatment of physics principles to cursory discussions that generally lacked detailed reasoning or evidence.

The new reform curricula developed by physicists, such as PSSC and Project Physics, struggled to gain market share from the dominant traditional texts and did make significant inroads; nonetheless, the new courses never enrolled more than a small fraction of all high school physics students. (Estimates vary widely, but figures under 25% are most plausible.[41]) Moreover, the number of courses that were *actually* new—as opposed to merely using the new texts without significant changes in instructional approach—is impossible to determine, but probably a relatively small proportion of the total.[42] The investment in time, resources, and professional expertise that had been put into PSSC and other curriculum development projects of this time had never been matched before—nor has it been since—in U.S. history. Nonetheless, the enormous potential for impact on U.S. physics education that had been envisaged by its creators was never fully realized. In any case, by the late 1980s, combined adoptions of the PSSC and Project Physics textbooks had dropped to around 10% of total adoptions.[43]

Changes were also occurring in physics instruction at the college level. A new textbook for the introductory course was published by Resnick and Halliday in 1960,[44] and it and its successors rapidly became the most popular and widely used college-level texts of the post-war era. In a manner analogous to that adopted by PSSC, the new text dropped many topics previously considered standard, while devoting longer, more conceptually detailed, and more mathematically sophisticated discussions to fundamental principles that emphasized the unity and modernity of physics. Practice problems emphasized algebraic and qualitative solutions, rather than ones that were purely numerical; "practical" applications (such as simple machines, pumps, electronics, and many others) were dropped, and unifying principles—including quantum physics—were developed with greater depth, generality, and mathematical rigor than ever before.[45]

H. Culmination of post-war reforms and emergence of modern PER, 1967–1991

This period incorporated the tail-end of various reform efforts launched during the late 1950s, and it also marked the emergence of physics education research (PER) in university physics departments and the regular and sustained publication of PER papers in physics journals.

In a major effort to improve the teaching of college physics, the Commission on College Physics had been launched in 1960, with NSF support, by leading physics educators under the auspices of AAPT; it also included officers of the American Institute of Physics (AIP).[46] In 1968, the Commission published a landmark study of high school physics teacher preparation, calling attention to the urgency of improving both the quality and quantity of physics teachers.[47] In 1972, the Physics Survey Committee of the National Research Council (NRC) published an extensive report endorsing the creation of inquiry-based college physics courses to prepare teachers of both high school physics and of elementary school science.[48] A key contributor to the NRC report was A. B. Arons, a physics professor at the University of Washington.

Arons and theoretical physicist R. Karplus, a physics professor at the University of California, Berkeley, were both influential in establishing the foundation for modern PER although neither engaged in it directly on his own. Both transitioned from traditional physics research into physics curriculum development (Arons in the 1950s, Karplus around 1960), but they developed their ideas largely independently of one another. Karplus contributed to PER by applying systematic and rigorous research methods to investigations of student learning, albeit with a focus on students' broader scientific reasoning processes rather than on learning of physics concepts *per se*. His curriculum development focused on science for elementary school grades K-6, and he also led workshops for high school and college physics teachers. Arons, although not interested in carrying out education research himself, contributed by carefully describing methods for recognizing, utilizing, and developing students' conceptual ideas in physics through inquiry-based curriculum design and assessment. Arons's focus was on developing inquiry-based physics courses for future elementary teachers.

Karplus and Arons were among the very first university physicists to put a primary emphasis on science curriculum development for elementary school (grades K-6) and on science education for grade-school teachers. (Essentially all of the previous focus had been on the high school course and high school teachers.) This work was greatly expanded by L. C. McDermott at the University of Washington in the 1970s with the development of physics curricula for both elementary and secondary teacher preparation, supported through systematic research on physics learning.[49] McDermott was a pioneer in developing curricula for making physics more accessible, especially to underrepresented populations,[50] through instructional interventions based on research about students' thinking in physics.[51] At around the same time, Arizona State University's D. O. Hestenes criticized the lack of participation of most physicists in K-12 education, and argued that faculty in colleges of education were not equipped to deal with the nuanced issues of content-specific learning; he called for increasing roles for physics faculty in K-12 education.[52]

Although a small handful of physics educators had investigated college students' learning in earlier decades, this period marks the true beginning of the field of physics education research in a university setting. During the 1970s, F. Reif and co-workers used physics as a context for investigating college students' problem-solving abilities.[53] At the same time, McDermott's group initiated systematic investigations of physics learning among university students in the U.S.,[54] while French physicist L. Viennot carried out systematic research on students' "spontaneous concepts" in physics.[55] In the 1980s, Hestenes and his colleague I. A. Halloun developed and published the initial version of the research-based Force Concept Inventory (FCI), a now widely used mechanics diagnostic test that has helped to expand awareness of PER among college and university physics faculty.[56] During this same period, physicists were engaging in pioneering work applying computer-based laboratory technologies to guided-inquiry instruction in the college physics classroom,[57,58] while others emphasized the importance of qualitative analysis using multiple representations (graphs, diagrams, words, etc.) in physics instruction.[59]

Although university-based physics educators (including Nobel laureate K. G. Wilson) were engaged to varying degrees with K-12 education, particularly through teacher preparation, towards the end of this period their focus—in distinction to earlier periods—had now clearly turned to college-level physics instruction.[60] Meanwhile, among the larger education community, publication in 1983 of the groundbreaking report *A Nation at Risk* catalyzed a series of national commissions, reports, surveys, and investigations that would lead eventually to major new initiatives and science "standards."[61]

I. Rise of conceptual physics and of modern PER, 1992–2001

This period saw the emergence and ascendance of two unprecedented and transformative phenomena in U.S. physics education: (i) significantly increased diversity in high school physics course offerings accompanied by dramatically rising physics enrollment; and (ii) the widening acceptance of contemporary physics education research in university physics departments. Diversity in the high schools included both new physics courses and the "rebranding" of older ones.

The percentage of high school graduates who had taken a physics course was at or near all-time historical lows of 16–18% in the mid-1980s. It then began a steady rise, reaching 31% by 2001 in an upward trend that has continued to the present day.[62] The largest single component of this rise was the rapid growth of the "conceptual" physics course, taught both in 9th grade and in higher grades, that emphasized qualitative descriptions and minimized use of mathematics. Although in some sense this was a re-branding of the "physics for non-science students" course previously taught in some schools, enrollment in this course—whatever its official name—skyrocketed by about an order of magnitude. This included enrollment in the new "Physics First" courses, which overwhelmingly adopted conceptual physics textbooks. Physics First was a movement to begin high school physics instruction in the 9th grade; it had a powerful advocate in L. M. Lederman, Nobel laureate in physics. The rise of enrollment in conceptual physics, however, actually predated the rise and expansion of Physics First. Moreover, a sizable fraction of so-called "regular" physics courses adopted the non-mathematical conceptual physics text.[63] A significantly increased popularity of Advanced Placement courses added to overall enrollments.

The rapid rise of enrollment in conceptual physics courses seems to have occurred without any deliberate planning or coordinated action at the state or national level. (This rise was accompanied by a dramatic increase in the popularity of Hewitt's text *Conceptual Physics: A High School Physics Program*, a high-school version of the text originally published in 1971.[64]) One reason for the rise may have been the steady increase in high school science graduation requirements imposed by the individual states, consistent with—if not directly motivated by—the recommendations in the 1983 report *A Nation at Risk*. That report recommended a requirement of three years of high school science for *every* graduate, a requirement met at that time only by a handful of states. With steady increases, by 2008 the number of states imposing the three-year (or more) requirement had risen to 31.[65]

Ironically, the institutionalization of new physics courses to supplement the standard, mathematically oriented "college-prep" course was a realization of one of the goals of physics education reformers of the early 1900s. However, the new and revised courses were strongly focused on physics concepts with both qualitative and quantitative problem solving (albeit with a notably reduced level of mathematical complexity). That is, they were *not* especially designed to emphasize (although they certainly did include) "practical applications," "everyday life," "science and society," or any of the other themes that had been suggested during the 1920s and 1970s as means for expanding interest and enrollment in physics. From a content standpoint, these courses were largely consistent with the latest sets of national science standards, the Benchmarks for Science Literacy (1993)[66] and the National Science Education Standards (1996).[67]

Quite separate from the developments at the high school level, this period also saw expansion of efforts by a modest number of university-based physicists to improve undergraduate physics instruction through systematic research on physics learning and teaching. Before the 1970s, by contrast, nearly all investigators who did research on physics education had focused on instruction at the K-12 level. The small handful of physicists who, in the 1970s, had begun to investigate learning by university physics students, had by 1989 grown to include faculty members at about ten research-intensive university physics departments. The number of faculty involved in PER—including junior faculty—increased significantly over the next dozen years. More than 90 PER papers were published in AJP during this period, a dramatic increase over previous levels. A wide variety of research-based curricular materials was produced and disseminated during this period, a few of them by major textbook publishers. A widely cited landmark study by R. R. Hake showed that, among students in courses using research-based active-learning instructional methods that were often inquiry-based, learning gains in mechanics were far higher than in traditional lecture-based courses.[68] Even "ordinary" textbooks published during this period often claimed to be based on research such as that being carried out by workers in PER. Another indicator of the rising influence of PER was that attendance at PER sessions at national AAPT meetings increased sharply during this period.

To support the research and development work, graduate students working towards Ph.D. degrees for research in physics education were increasingly brought into the process; some received their degrees in the physics departments and others from colleges of education, although most of the work and faculty advising was centered in physics departments. During this period, graduate student involvement in physics education research would increase by a factor of four or more. Annual national meetings of physics education researchers were initiated and grew in popularity.

Several of the university-based physics education research groups incorporated physics teacher education as a part of their mission. However, their various courses, programs, and workshops could reach only a tiny fraction of the approximately 1400 new physics teachers hired each year in U.S. high schools.[69] Their impact on a national level, therefore, was very limited. An exception to this was the growing program in "Modeling Instruction" for in-service teachers founded by Hestenes at Arizona State University in 1990 and expanded nationwide beginning in 1995. Through an ongoing series of summer workshops that gradually spread throughout the nation, as former workshop participants became workshop leaders themselves, the cumulative number of participants grew into the thousands. By 2014 the total number of unique participants had exceeded 6500, with about 85% being high school teachers and the remainder middle school teachers.[70] (For comparison, AIP estimated that the total number of U.S. high school physics teachers in 2009 was 27,000.[71]) In a 2005 survey of high school physics teachers, the Modeling Instruction materials and the University of Washington's research-based *Physics by Inquiry* curriculum were each reported as "formally" used "in place of more traditional instruction" by 6% of teachers surveyed.[72]

J. The present day: High school physics and national reports, 2002–2014

Throughout this most recent period many trends from previous decades have persisted while some new themes have emerged. Enrollments in high school physics continued to rise; by 2012 approximately 80% of the age-17 population was graduating from high school, and about one third of that population had taken physics. Both of these figures marked all-time historical highs for the population as a whole, although the percentage of *high school students* taking physics is still far below the historical peaks achieved more than a century ago (see Fig. 1 and Table I). Both conceptual physics and Advanced Placement physics courses continued to increase in number, and a "dual-track" system of conceptual (non-mathematical) physics versus regular/honors physics grew to dominate the scene. In effect, a substantial fraction of present-day high school physics students are excluded from study of mathematically oriented treatments of physics, although one could argue that most of them would not otherwise have taken physics at all.[73,74]

Continuing a long-time tradition, numerous national reports and commissions called for increased emphasis on improving high school science education. The NRC's Committee on High School Science Laboratories included among its members Nobel Prize winning physicist C. E. Wieman; the Committee's 2006 publication *America's Lab Report* called for increased engagement of students in science laboratory activity and increased attention to the preparation of teachers to facilitate investigation-based laboratory work in the classroom.[75] For the first time since the 1960s, multiple Nobel prize-winning physicists were taking on a leading role in efforts to reform high school science instruction.

Yet another version of national science standards was developed: the "Next Generation Science Standards" (NGSS) continued a tradition initiated by the 1993 Benchmarks for Science Literacy [Project 2061] and the 1996 National Science Education Standards.[76] The NGSS included (a) core science concepts, (b) a specific scientific practice relevant to each concept, and (c) "crosscutting concepts" (referred to as "common themes" in the Project 2061 Benchmarks), such as scale, systems, and models. In contrast to previous practice, a majority of the 50 states made a commitment to "give serious consideration" to fully adopt the new standards, and some funding was provided by the federal government for the development of national assessments linked to the NGSS.

As our discussion has shown, recommendations issued by various national commissions and professional organizations have, for over 130 years, stressed the importance of improving U.S. science education. However, the urgency expressed by reports during this most recent period has been matched only a few times in previous history (e.g., during the 1950s). This urgency was ostensibly driven by findings from international comparative assessments such as the Third International Mathematics and Science Study (TIMSS)[77] and the Programme for International Student Assessment (PISA),[78] both of which indicated that the United States was being outperformed by other nations in pre-college mathematics and science education. Reports such as the NRC's "Rising Above the Gathering Storm"[79] and PCAST's "Engage to Excel"[80] incorporated slogans such as "Ten thousand teachers, ten million minds," and "Producing one million additional college graduates with degrees in science, technology, engineering, and mathematics (STEM)"; these and many similar reports stressed the urgency of increasing the number and quality of STEM teachers and STEM majors. A theme repeated from many previous eras was the need for improved science education to prepare students to engage with an increasingly technology-focused economy. Despite its well-worn familiarity, this theme received fresh support from various studies that indicated that increasing proportions of future jobs would require high levels of technical background.[81]

The field of physics education research has continued to expand: the number of physics departments including tenured or tenure-track PER faculty was 60 or more by 2014. PER publications in AJP and Physical Review are now appearing at a rate of 50–80 per year while the annual peer-reviewed Proceedings of the Physics Education Research Conference has grown to over 400 pages. Physicists' engagement in educational reform activities rose to levels rarely matched and never exceeded in the past; the activities included focused efforts to improve high school teacher education as well as to transform college physics through evidence-based approaches. Results from PER were increasingly incorporated or acknowledged in national reports such as the PCAST report. The NRC commissioned reports on Discipline-Based Education Research (typically conducted by university-based researchers in the disciplines of physics, chemistry, biology, mathematics, and engineering)[82] and on the state of undergraduate physics education and physics education research.[83] A Special Topics section of the premier journal Physical Review, published by the American Physical Society (APS), was launched in 2005 with the title Physical Review Special Topics - Physics Education Research. The Physics Teacher Education Coalition (PhysTEC) was developed by the APS in 2001 in partnership with AAPT; it focused on attracting physics faculty to discussions and activities related to physics teacher education. In 2008, in collaboration with AIP, PhysTEC launched the "Task Force on Teacher Education in Physics" (T-TEP) which, after four years of study, published the 130-page report *Transforming the Preparation of Physics Teachers: A Call to Action*.[84] This was joined by two other publications, *Teacher Education in Physics: Research, Curriculum, and Practice*[85] and *Recruiting and Educating Future Physics*

Teachers.[86] Again, not since the 1960s had APS made such a concentrated effort to focus attention on improving the state of high school physics education.

It is reasonable to ask whether and to what degree this new surge of physicists' educational activities has impacted student learning at the national level, both in high school and in college. It is too early to provide more than suggestive data. First, hundreds of careful studies have documented improved physics learning in individual courses and programs in which research-based materials have been used (see, e.g., Ref. 1.) Long-term longitudinal studies of diagnostic exam data for introductory college physics students in Minnesota and Colorado have shown slow but steady increases in pretest scores, which may or may not be indications of improved physics instruction at the high school level.[87] At this time, however—lacking national surveys to address this issue—little more can be said.

III. SUMMARY

Since the late 1860s there have been ongoing efforts to make lasting change in how physics is taught, both at the college and the high-school level. From the Report of the "Committee of Ten" in 1893 to the post-Sputnik curricular reforms of the late 1950s and on to the present day, college- and university-based physicists have been deeply involved in high school physics and physics teacher preparation. Educational reforms at the high school and college levels have had mutual influence and impact on each other. A recounting of this history leads inevitably to certain thematic questions: What strategies might have potential to improve physics education on a broad and lasting basis? Have any of the previous strategies led successfully to lasting impacts? Has anything really changed?

Although there are many similarities in the themes for each period throughout the 150-plus years described here, there have also, indeed, been some important changes in physics education. One clear difference between the earlier events and those of more recent periods is the development of PER at the college level. PER is largely carried out by physicists who are career researchers and teaching practitioners themselves. This has led to deeper knowledge of the process of physics learning and has contributed to changes in college textbooks and other instructional materials, as well as to the development of instructional strategies informed and validated by educational research. The dynamics of education reform have shifted to include college physics instead of only (or primarily) high school physics, and indeed the focus of most recent reform efforts has been at the college level. At the same time, recent reforms in high school science have largely focused on increasing the availability of engineering and technological curricula, rather than on physics, chemistry, and biology courses, as was the case in the early to-mid 1900s.

Many things have simply not changed since the early 1900s. There continue to be severe practical and logistical challenges to implementing research-based hands-on, active-learning, lab-based instruction on a broad scale, at every level—K-12 through college. As was the case in the early 1900s, there is substantial and widespread dissatisfaction with the way physics is currently taught (at least as expressed in the literature). Meanwhile, there continues to be the challenge of adequate teacher preparation, which is largely conducted or directed by science educators who tend to downplay physics-specific pedagogy and instead emphasize methods appropriate for "general science."

There remain many unanswered questions. For example:

1. Despite the widespread and long-standing support for the "inductive" method of instruction—referred to by various names such as "inquiry," "scientific practices," etc.—there has never been any successful, long-lasting, and broad-based implementation of this method either in high school or college physics courses. How can one account for the persistent failure to implement a method that seems to have had such broad and continuing support? Is it simply that these desired methods are, logistically and practically, so much more difficult to integrate into normal classroom practices?
2. PSSC and Project Physics mark one time in history when large-scale national reform in physics education appeared possible. How did this come about? Was it simply ascribable to specific effects of the Cold War, or were there general conditions that might have relevance in other historical circumstances? Why did it not take hold to any lasting degree, despite the enormous efforts and resources thrown into the project? Are there current resources and ideas that might make it possible to emulate the far-reaching initial impact of PSSC and Project Physics, yet with a sustainable model that retains and expands upon that initial impact to have more lasting effects?
3. Can modern PER's focus on students' understanding of physics concepts lead to changes in educational reform different from those we have seen in the past?
4. More broadly, is there now—or was there ever—a consensus among physics educators as to the most important goals of physics education? Is it primarily to teach practical, factual knowledge? To convey a deep understanding of fundamental principles? To develop appreciation of, and facility with, the use of scientific methods? Can there be true consensus on effective reform methods if there remain fundamental disagreements about pedagogical goals?

This is just a sample of the many historical questions that, if answered, might illuminate a path toward more effective pedagogical reform. As we move forward in physics teaching and in research on student learning, it is important to be aware of past efforts, to recognize what is different between the past and the present, and to make informed decisions about research and teaching agendas on the basis of this recognition and awareness.[88] In every period studied, regardless of differences in details or personalities, one theme that has persisted is a deep concern for improving access to and understanding of the principles and processes of physics. It is this theme, perhaps, that continues to drive forward the long-lived and perhaps never-ending process of physics education reform.

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[a]Electronic mail: david.meltzer@asu.edu
[b]Electronic mail: valerie.otero@colorado.edu

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Spinthariscope

Alpha particles impinging on a screen coated with zinc sulphide will produce tiny flashes or scintillations of light. William Crooks (1832-1919) was one of the discoverers of the effect in 1903, along with Julius Elster and Hans Geitel. The spinthariscope (from the Greek word for *scintillation*) is a brass tube with a magnifying eyepiece at one end and a screen of zinc sulphide at the other. A small thumb-wheel allows the alpha particle stream from a uranium compound to be directed toward the scintillator. When used in a dark room, bright flashes may be seen with a dark-adapted eye. This instrument, only 3.3 cm in length, is marked “Spinthariscope / W. Crookes / 1903 / R. & J. Beck, Ltd London”. It is in the Greenslade Collection. (Notes and photograph by Thomas B. Greenslade, Jr., Kenyon College)