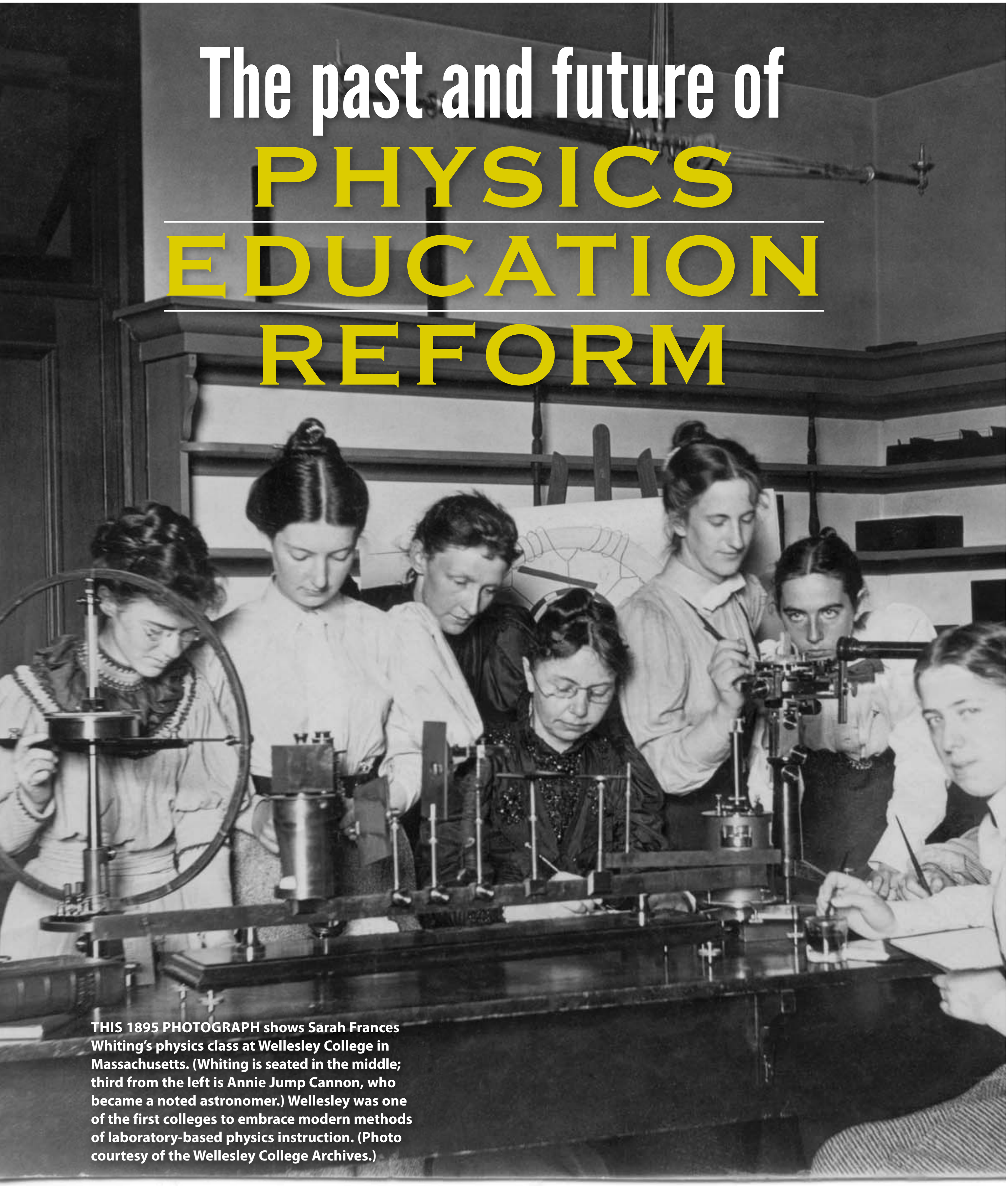
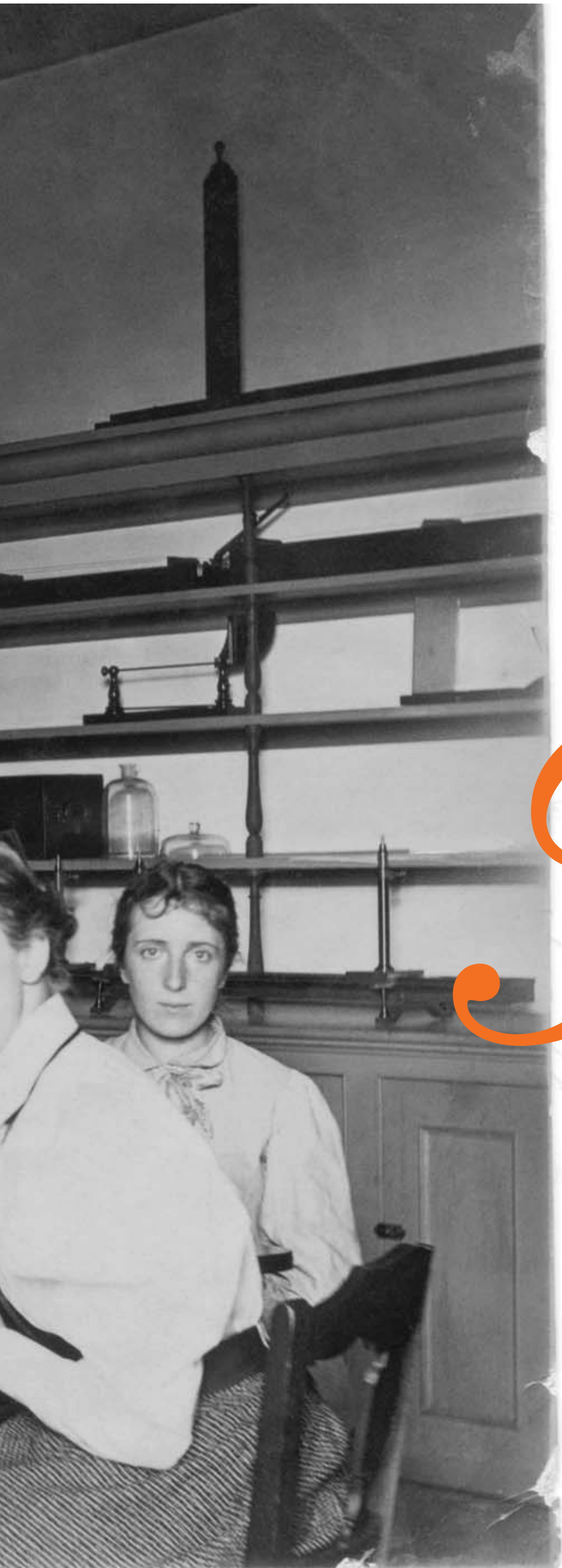
The past and future of PHYSICS EDUCATION REFORM



THIS 1895 PHOTOGRAPH shows Sarah Frances Whiting's physics class at Wellesley College in Massachusetts. (Whiting is seated in the middle; third from the left is Annie Jump Cannon, who became a noted astronomer.) Wellesley was one of the first colleges to embrace modern methods of laboratory-based physics instruction. (Photo courtesy of the Wellesley College Archives.)



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The Every Student Succeeds Act, passed in 2015, harbors both threats and opportunities for physics education in the US.

For almost as long as physics has been part of the high school curriculum, physicists have sought to change the way it's taught. As University of Chicago physicist Charles Mann wrote in the journal *School Science and Mathematics* in 1906,

> When science was introduced into the schools, it was naturally taught . . . dogmatically and deductively. But it is now time for us to realize that science is our process of interpreting natural phenomena. . . . Hence if young people are to become adepts in science, they must be taught how to interpret for themselves. They should develop the habit of making sound interpretations of phenomena—a habit which can be acquired only by scientific study.[1]

Mann's vision echoes those of countless physicists who came before and after him. Yet today—some 200 years after physics, then known as natural philosophy, began to be taught in secondary schools—that vision has yet to be fully realized. A major impediment has been a lack of effectively prepared physics teachers. Throughout the 1800s and 1900s, both physicists and teacher educators made efforts to transform and improve precollege physics teaching and physics teacher education, with only limited results. As physicists and federal policymakers alike have recognized, the outcomes have been unsatisfactory. (See the time line on page 52.)

On 10 December 2015, President Barack Obama, pictured in figure 1, signed into law the Every Student Succeeds Act, with hopes that it would lead to, among other things, dramatic improvements in the preparation of public-school teachers. The law is the latest chapter in a centuries-old saga; its potential impact can't be fully understood without first stepping back to discuss the chain of events that led to its creation. We will briefly outline those events here and explore some of the many factors that have landed us in the present situation. Although the overt objectives of the new legislation diverge from the consensus recommendations advanced by the physics community, and there is a significant risk of unintended consequences, the law presents an opportunity to realize a long-deferred vision of physics reform.

The road to ESSA

The Every Student Succeeds Act (ESSA) promised to address some of the unintended consequences of its predecessor, the 2001 No Child Left Behind Act (NCLB). That act was intended to provide equal opportunity for all students by holding schools accountable for student achievement. But by evaluating schools heavily on standardized test scores—with little regard to economic and social disparities—the NCLB effectively punished schools for outcomes largely beyond their control. More class time was devoted to test preparation, less to learning. Law-mandated school closures demoralized students, teachers, and communities.[2]

Although the unintended effects of the NCLB influenced the language in ESSA, so too did a different entity: a nonprofit known as the NewSchools Venture Fund (NSVF). That fund invests heavily in charter-school management. In essence, it seeks to replace the current public education system with one that is deregulated, market based, and less beholden to public oversight. Such a system would emphasize privately run, privately funded entrepreneurial programs. The fund's educational efforts focus heavily on increasing standardized test scores and on decreasing the formal qualifications required of teachers and teacher educators.[3]

The NSVF strongly influenced the development of the 2013 Growing Education Achievement Training Academies for Teachers and Principals (GREAT) Act. By that time, the US Department of Education had begun issuing policies and public statements reflecting distrust in university-based teacher education programs—particularly those in schools and colleges of education—and the GREAT Act sought to open pathways for the private sector to generate a decentralized, market-based teacher education system. Although the legislation failed to pass through Congress, many of its intents and policies were fixed into law through ESSA.

Among the eight titles that make up ESSA, Title II, "Preparing, Training, and Recruiting High-Quality Teachers, Principals, or Other School Leaders," is particularly consequential. The purported aim of Title II is to increase student achievement and improve the quality and effectiveness of teachers. However, it actually provides legal justification for decreasing or minimizing teacher requirements, including content-area requirements for teachers in specialized subjects such as physics. The practice of relaxing physics training requirements for people who teach physics has informally persisted as long as the subject has been part of the public school system—and it has been bitterly and consistently criticized by physicists.

Title II of ESSA permits states to divert a portion of federal education funding to the creation of so-called teacher preparation academies. Such academies must adhere to certain strict policies: They cannot obligate faculty to hold advanced degrees or conduct academic research; they cannot impose restrictions related to the number of course credits required as part of their programs of study; they cannot impose restrictions related to undergraduate coursework for individuals seeking teacher licensure or credentialing, provided the individual has passed state-approved content-area examinations. The legislation sets in motion provisions for academy graduates to receive "at least the equivalent of a master's degree in education," despite potentially having never earned a bachelor's degree of any kind.

If a state allows academy graduates to teach physics, those graduates may do so without ever having taken any undergraduate physics or mathematics courses. It would be left to

THE TEACHER-PREP PROBLEM IN PHYSICS, OVER THE YEARS

"Many [educators] emphasize the difficulty of getting proper teachers for this subject, both for the schools and for the colleges; for the teacher should have a knowledge far exceeding the amount he must teach." (Ref. 4, C. K. Wead, p. 125.)

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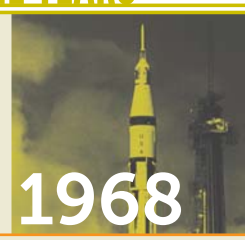
"Many teachers, especially those new to the kind of work required, have too little knowledge of their subject, many school boards are unwilling or unable to give the teacher proper facilities and needed assistance." (E. H. Hall, *Science* **30**, 577, 1909, p. 585.)

"The problems arising from a deficiency in the number of well-trained science teachers in the secondary schools are as much the concern of the school systems as they are of the teacher training institutions." (*Am. J. Phys.* **14**, 114, 1946.)



NASA

"It is our continuing failure to provide anything like enough trained high school physics teachers that causes high schools to draft others for the job." (Commission on College Physics, *Preparing High School Physics Teachers*, U. Maryland, 1968, p. 5.)

LUCAS TAYLOR/CERN

"The preparation of qualified physics teachers has failed to keep pace with a dramatic increase in the number of high-school students taking physics. Consequently, more students than ever before are taking physics from teachers who are inadequately prepared." (Ref. 16, p. xi.)

FIGURE 1. PRESIDENT BARACK OBAMA, joined by members of Congress and other guests, signed the Every Student Succeeds Act into law on 10 December 2015. (Photo by Amanda Lucidon.)

the free market to determine whether schools and school districts hire physics teachers with, say, bachelor's degrees in physics or academy graduates who may never have formally studied physics at all. And that was precisely the intent of the legislation's designers—to allow market forces, rather than content-area experts, to determine how teachers of physics and all other subjects are prepared.

It's too early to know how states will proceed; we are not yet aware of any formal decisions to establish statewide teacher preparation academies. Newly appointed secretary of education Betsy DeVos is a well-known advocate of private, entrepreneurial education initiatives, and thus it would not be surprising to see the Department of Education encourage, if not directly support, alternative teacher education pathways.

What will this mean for physics education? Although it is difficult to predict outcomes of any physics teacher preparation system, an examination of historical trends can provide some insight. To that end, we now turn to the lengthy history of efforts to reform both physics education and the education of physics teachers.

Unanswered calls for reform

Throughout the late 1800s and early 1900s, physicists and teachers lobbied successfully to deemphasize lectures in physics curricula, especially in high schools, and expand the role of laboratories and projects that actively engage students.[4] Physicists and other scientists advocated for instructional methods that immersed students in the spirit of investigation and discovery, as exemplified in an 1881 report by Frank Clarke: "Every branch of knowledge should be so taught that the pupil may catch some of its real spirit, something of that feeling which animates and encourages the foremost investigators, and which alone is able to cause a vigorous growth."[5]

Between 1880 and 1900, the use of hands-on student laboratory activities increased dramatically, at both the high school and the collegiate levels. In 1906 the Central Association of Science and Mathematics Teachers (now the School Science and Mathematics Association) commissioned a committee of one physicist (Mann) and two high school physics teachers to do whatever was necessary to "make the elementary courses in physics more interesting and inspiring to the students."[6] The committee surveyed teachers throughout the US to determine which experiments and classroom activities were best suited to engage students in physics. The committee hailed a "new movement among physics teachers," evident in publications and symposia aimed at understanding how to emphasize "the development of habits of scientific thought" and "the method by which science obtains its results" rather than "more or less scattered facts and theories" taught in such a way that they could only be committed to memory.[7]

That theme has been a recurring one, with various science education reformers seeking to emphasize "the inductive method," "scientific inquiry," or the "nature of science"—all terms for the exercise of engaging students in science as a practice and as an evidence-based way of understanding the world. Reform efforts have come and gone, each new group of reformers paying little attention to the writings and actions of their predecessors.[8] Today the fashionable term is "scientific practice," as exemplified in the National Research Council's 2012 *Framework for K–12 Science Education*:

> Our expectation is that students will themselves engage in the practices and not merely learn about them secondhand. Students cannot comprehend scientific practices, nor fully appreciate the nature of scientific knowledge itself, without directly experiencing those practices for themselves.[9]

The science practices in the 2012 framework bear much resemblance to those promoted two decades earlier by the American Association for the Advancement of Science.[10] And they are not unlike the practices described by physics educators as early as 1884. More than 130 years of published articles and reports have consistently called for students to more deeply engage in the practice of inducing principles from data, the so-called inductive method.[4] Remarkably, despite more than a century of broad agreement among physicists on the type of instruction that should take place in physics classes, such instruction has yet to be achieved in the majority of US K–12 classrooms. There are many reasons for that failing, and we do not mean to minimize the complexity of the problem. Nonetheless, it is important to understand the nature and scope of the challenge.[11]

While different terms and buzzwords have come and gone, three aspects of physics education, and science education more generally, have remained unchanged: Scientists have persistently called for a very specific type of instructional change; most teachers have received little preparation to teach specific science content, despite ardent protests by the scientific community (see figure 2); and current reformers have failed to acknowledge similar efforts and issues from previous times.

Recurring obstacles

To the extent that anyone supervises the educational development of physics majors who seek to become teachers, it is often colleges of education. For example, although only around 30% of US physics teachers have a bachelor's or master's degree with a major field of study in physics, a narrow majority of that group stated on recent surveys that their physics degrees were awarded by schools or colleges of education.[12] That doesn't necessarily mean that their physics classes were taught outside the physics department. But it may imply that their curricula were heavily weighted with education courses and that an education school had final authority over their curricula's design.

Professors in education schools often lack backgrounds in graduate-level science research, and therefore generally do not have the experiences necessary to interpret fully the intention behind instructional goals promulgated by professional scientists. Such goals typically focus on engaging students in the inquiry-based, inductive process associated with laboratory investigations and on guiding students to experience "the spirit of science." Most policymakers who develop and pass legislation directly affecting precollege science education also lack experience engaging with science in ways consistent with scientists' calls for reform. The combination often leads to the propagation of curricula and legislation that are unhelpful at best and deeply harmful at worst.

Conversely, when curricula or standards designed by scientists are disseminated to policymakers and teacher educators, the reform efforts often run aground on misinterpretations and faulty implementations that fail to capture the designers' intentions. Those misinterpretations can play out in any number of ways. Recently, for instance, some teacher educators have expressed confusion regarding the meaning of terms such as "science practices." Wrote one educator, "'Science practice' is not well defined in the field of science education. While we agree that students should engage in 'authentic' science activities, there is little consensus about the specific dimensions of disciplinary work that students should learn."[13] The truth, as outlined above, is that physicists and other scientists have long reached consensus regarding broad goals for relating classroom activities to the practices of science.

Many teacher education faculty members have criticized "scientific inquiry," "nature of science," and similar terms as overly specific, prescriptive, and implicative of an immutable set of rules of reasoning and action that students must learn to follow.[14] In fact, as scientists well know, none of those terms—whether uttered in 1910 or in 2010—was ever intended to refer to a prescriptive, rule-based process.

More troubling still, some science teachers and teacher educators have interpreted scientists' goal of teaching science concepts through inquiry as teaching *about* the nature of science—without any anchoring in specific subject matter. That leads to teaching context without content, which clearly was not scientists' intent. Such misinterpretations have persisted in the science education literature for decades; they have contributed to a perpetual cycle in which old terms are continually displaced by supposedly more precise ones, and old ideas are continually recycled and hailed as new. Although there are many possible reasons for the phenomena, a lack of adequate content-area knowledge among teachers and teacher educators is certainly one.

Another misconception that has persisted since the early days of physics education is an alternative interpretation of the intent of science education reform efforts that we refer to as the technology-applications worldview. In that ubiquitous worldview, scientists' proposed emphasis on project and laboratory methods of teaching is misread as a proposed emphasis on the application of established scientific fact to everyday technologies or social issues. In the early 1900s, that misconception led to a focus on understanding how technologies such as heating, power, and electrical lighting systems work; in 2015 it manifested as a focus on engineering design projects, many of which appropriated the STEM (science, technology, engineering, and math) acronym.

In one variation of the technology-applications worldview, students engage in evidence-based debates of socioscientific issues. They apply established scientific facts to controversial moral and ethical issues such as, say, stem-cell research or marijuana safety.[15] Because the investigations are primarily focused on technologies, social issues, and isolated scientific practices such as argumentation or modeling, they typically are not well adapted to the process and spirit of scientific discovery as generally understood by scientists. In fact, in the early 1900s, many proponents of the technology-applications worldview shunned what was then called special sciences and what is now often referred to as scientific silos—specialized courses in physics, chemistry, biology, and Earth science.

On the positive side, the technology-applications worldview addresses the long-standing goal of applying science to students' everyday lives. What it omits, however, is the human experience of discovery that is the main driving force in the lives of practicing scientists. It is precisely that experience of discovery that professional scientists intend to communicate with terms such as "induction," "inquiry," and the "nature of science."

The practical effect of the technology-applications worldview has been diversionary—or even oppositional—to the broader goals embraced by the scientific community. It is one of several factors that have complicated physicists' attempts at educational change. Although no one would deny the value of learning about the manifold technological applications of science, the scientific community is uniquely responsible for up-

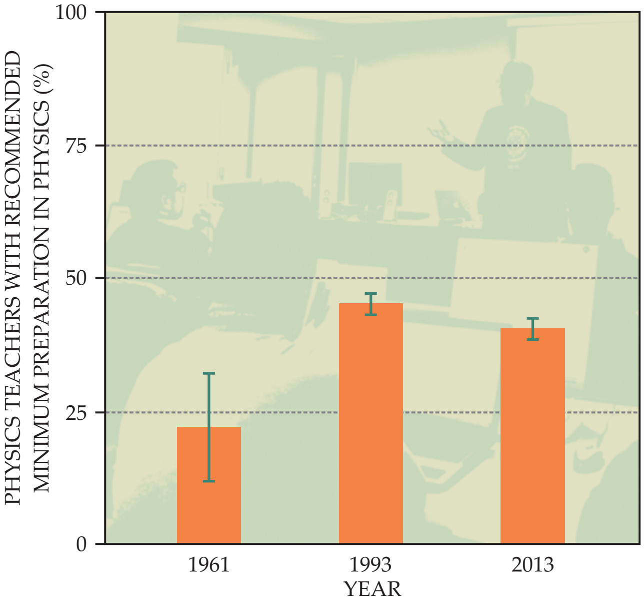


FIGURE 2. THE RANKS OF US HIGH SCHOOL PHYSICS TEACHERS trained in physics have grown over the past several decades, but fewer than half have the minimum 24 credit hours of physics preparation recommended by the Commission on College Physics. For the 1993 and 2013 data shown here, that fraction is approximated as the proportion of teachers who had earned either a major or minor in physics or physics education and error bars represent 95% confidence intervals. (For the 1961 data, error bars indicate the fraction of teachers having between 18 and 29 credit hours.) Older, statewide surveys suggest that, in the years before World War II, fewer than 20% of physics teachers had the recommended preparation. (Data from ref. 18.)

holding the *experience* of science as an equally if not more valuable element in the education and empowerment of members of modern society. The challenge, then, is to prepare hundreds of teacher educators and thousands of precollege teachers to experience science in ways consistent with scientists' long-held educational goals. Without such focused efforts, national-scale reform of science instruction is unrealistic.

Leveraging the law

By potentially expanding the ranks of physics teachers who lack physics experience, ESSA risks widening the philosophical gulf between practitioners and teachers of physics. But the legislation may also have a silver lining: It potentially opens new avenues for the physics community to develop physics teacher preparation academies.

In 2008 the American Physical Society partnered with the American Association of Physics Teachers and the American Institute of Physics to form the Task Force on Teacher Education in Physics (T-TEP), charged with studying the challenges of physics teacher education in the US. Their final report, issued in 2012, contained a dozen recommendations for physicists, physics education researchers, and education faculty, and it included a proposal to establish regional centers for physics teacher education. Those centers would be headed by scholars trained in physics, physics education, and physics education research.[16]

In theory, ESSA-funded teacher preparation academies could function as regional centers like those envisioned by T-TEP. By taking back responsibility for physics teacher education, physics departments—in cooperation with such academies—might be able to build state-supported programs based on physics content and physics practice. Such programs would have the pedagogical expertise necessary to educate teachers in methods consistent with physicists' long-held educational goals, although the academies' requirements would have to be couched artfully, in language that wouldn't conflict with the letter of the ESSA law. The necessary human and financial resources for such an endeavor are more readily available today than at any time in the past.

A case in point is the American Physical Society, which has in recent years engaged assertively with the K–12 education process. Up until 2015 the society offered scholarships to prospective teachers through its Physics Teacher Education Coalition (www.phystec.org), and it continues its long-standing program of awarding grants to universities that show dedication to physics teacher preparation. (See the article by Ted Hodapp, Jack Hehn, and Warren Hein, PHYSICS TODAY, February 2009, page 40.) For physicists carrying out their own research programs, however, devoting time to issues in physics education remains a logistical challenge.

Another advantage enjoyed by the physics departments of today over those of yesteryear is the prevalence of physics education research (PER) scholars. Those scholars typically have been educated in physics, have done graduate-level research in physics, and have chosen to apply scientific standards of evidence to investigations of how people learn and teach physics. PER scholars study students' understanding of physics ideas, students' reasoning processes and problem-solving approaches, the participation and achievement of students from underrepresented groups, the preparation of physics teachers, and methods and tools for assessing physics comprehension. They often work to design research-based physics curricula, which they then subject to thorough and repeated testing. They regularly publish their work in scholarly journals such as *Physical Review Physics Education Research* and the *American Journal of Physics*.[17]

The wealth of laboratory experiences that most physics departments make available to physics majors, some of whom become teachers, is another important resource. Ranging from verification labs to more authentic inductive experiences, those laboratories provide a rich context for helping undergraduate students experience the intellectual challenge and beauty of scientific research—to catch the "spirit of science," so to speak. The same is true of specialized programs such as the NSF-funded Research Experiences for Undergraduates, which provides more substantive, longer-term research exposure.

The years-long investigation by T-TEP demonstrated a need for designated point persons—or, in the words of the task force, champions—who can work to ensure that physics departments' resources are marshaled effectively in teacher preparation efforts. The task force found that highly productive teacher education programs invariably had at least one such champion.[16] That person worked to ensure, for example, that when various laboratory and research experiences were included in the teacher preparation process, they could be translated by prospective teachers into pedagogical knowledge and into practical instructional techniques for precollege classrooms. Some PER scholars are specifically interested in such work. The scholars also have the skill set needed to carry out investigations necessary to make and support claims about teaching and learning in physics. Along with other physics faculty, PER scholars could have a strong, positive influence on science education by partnering with teacher education academies to engage future teachers and teacher educators in first-hand scientific inquiry.

What would a collaboration between a physics department or national lab and a teacher preparation academy look like? Which university policies might need to be modified to accommodate such a collaboration? What would be the business model, and how would funding be distributed? As is the case with any complex system, the solutions aren't obvious. But if physics departments do not take action, the process will be left to nonphysicists, and we may be doomed to repeat history yet again.

We thank Joanna Behrman for bringing our attention to the photograph used on this article's opening page and Susan White for discussion of the data used in figure 2.

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