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Teaching physics for tomorrow

Equipping students to change the world

Crystal Bailey and Douglas Arion

Why should engineers have all the fun?

O

n a fine spring day in a hotel in downtown Washington, DC, a conference room full of educators listen raptly to a group of undergraduate students. One by one the students describe new technologies they developed—a process for eliminating fossil fuels from the production of synthetic materials or smart clothing that detects the physiological precursors of meltdowns in autistic children—and the companies they launched to market those technologies. Students recount how creating their product and launching their business was a deeply empowering and fulfilling experience, despite the hard work and uncertainty. They articulate how meaningful it is to create technologies that can improve human life.



Every student in that room is an engineering major; not a one a physics major.

Such was the scene at the March 2019 Open conference, held by an organization called VentureWell, where educators from across disciplines gathered to learn the latest in the pedagogy of innovation and entrepreneurship. The absence of physics students was odd, considering that so many major technologies that significantly affect human life started through research in physics. Wouldn't it make sense to see physics students applying their physics knowledge and ability to solve real-world problems?

Those trained in physics are able to solve problems, to apply mathematical and modeling skills, and to integrate and apply multiple technologies; their abilities make them particularly sought after by employers in many industrial and research environments. Only 5% of physics bachelor's degree recipients will ultimately become tenured physics faculty; the rest will apply their skills in a diverse range of careers, the vast majority in the private sector.¹ The same is true for recipients of physics PhDs. More than 60% of them also work in nonacademic environments.² If physics students received intentional training in innovation and entrepreneurship, and if they developed the mindset and vision to apply their skills, think of all the world's problems that could be solved!

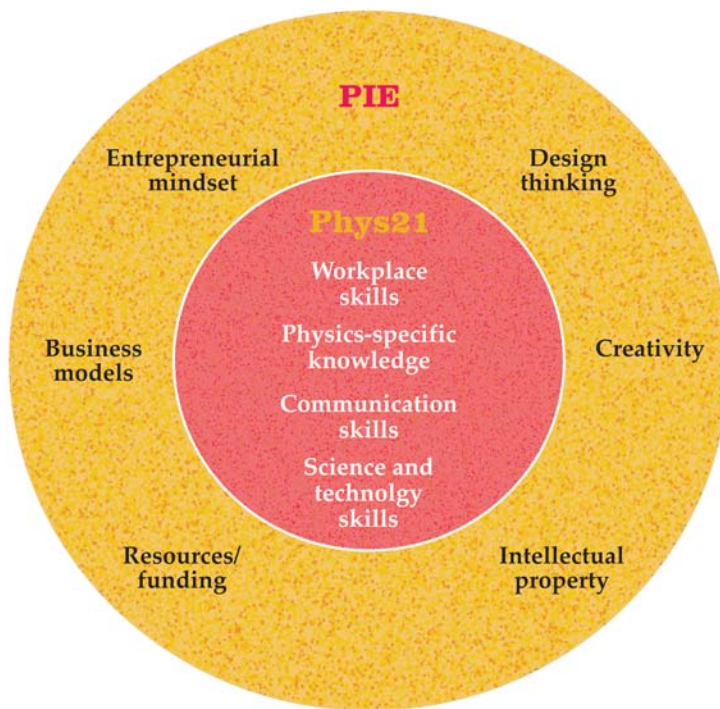
Besides enhancing student skills and opportunities, other factors make innovation and entrepreneurship education even more important now. Pressure is increasing on undergraduate education to produce financial value for graduates, especially as more and more first-generation students from diverse cultural backgrounds enroll in college. The closures of Mount Ida College, Daniel Webster College, and Green Mountain College and the search by Hampshire College to find sustaining partners bring home the message: Colleges have to adapt if they are to survive.

Seven years ago, a group of individuals met serendipitously at a session at the March Meeting of the American Physical Society (APS) that focused on careers. There they discovered a shared and deeply held interest in developing a new approach to teaching physics, one that intentionally taught the skills, knowledge, and mindset to equip physics students to have more impact as scientists in the workforce. From that initial meeting, an informal working group formed. It has since blossomed into a community of practitioners of what we call physics innovation and entrepreneurship (PIE) education.

What PIE is—and what it isn't

PIE consists of experiences, courses, and research opportunities that convey leadership, communication, and other professional skills; that develop deep technological expertise and the confidence to translate it into innovative solutions to problems; and that create familiarity with intellectual property, return on investment, and other workforce-relevant concepts—all in the context of an undergraduate physics degree. PIE encompasses many of the skills and knowledge that will be relevant to future careers, but it also includes the mindset and knowledge that will enable physics students to recognize opportunities to address human needs and to translate their ideas into scalable solutions.

Don't be misled by the presence of "entrepreneurship" in PIE. Few physics students will go on to start their own compa-



THE SCOPE OF PIE (physics innovation and entrepreneurship) encompasses the recommendations of *Phys21: Preparing Physics Students for 21st-Century Careers*, the 2016 report of the Joint Task Force on Undergraduate Physics Programs.

nies. Even so, all students will benefit from understanding how to create value propositions, marshal funding and other resources, manage teams, think strategically, and deal with uncertainty. That's because the majority of them are destined for the private sector. And those students who do have entrepreneurial dreams will be far better positioned to realize them. What's more, the same skills are often essential for success in academic research environments. Integrating them into the physics curriculum will also serve the 5% of physics undergraduate degree recipients who pursue academic careers.

Despite the manifest benefits of PIE, faculty members wonder how they can incorporate its ideas while struggling with ever-tightening budgetary and time constraints. They also worry about preserving the "soul" of physics as a discipline. One of the earliest conversations our working group had with skeptical faculty members took place in 2015 at a panel on PIE at the APS March Meeting. Most of the attendees were undergraduates, graduate students, and postdocs, the demographic which tends to be in the majority at events with "entrepreneurship" in the title. However, a small number of highly engaged—even combative—physics faculty were also present. They voiced two major questions. Are you advocating turning our physics students into engineers? What physics will I leave out in order to teach PIE instead?

Since that session, the growing community of PIE practitioners has been continually revisiting the two questions. In short, the answer to the first question is no. The mathematical facility, problem-solving ability, and breadth of technical expertise that are hallmarks of physicists and distinguish them from engineers are what make physicists powerful innovators; they are enhanced through PIE education, not depleted. The answer to the second question is that PIE can be incorporated into the student experience in ways that do not reduce the qual-

Box 1. Examples of Curricular Materials

PIE Modules for Introductory Physics Courses

Led by Bahram Roughani
Loyola University Maryland (LUM)

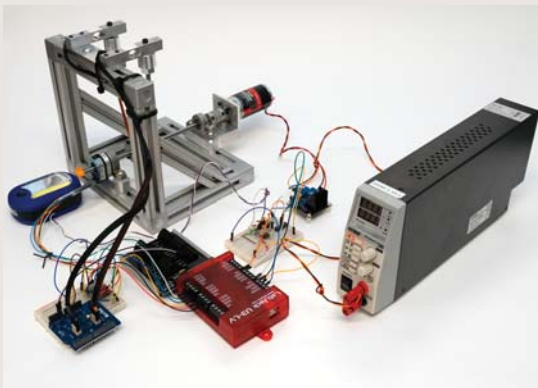
These modules use design-thinking, which includes creative and appropriate attention to human needs while demonstrating the application of physics knowledge in real-world, human-focused applications. One module is based on the Hyperloop, the high-speed transport system proposed by a joint team from Tesla and SpaceX. Another module is based on a series of problems and exercises around human-powered pumps that have been developed and subsequently used for irrigation in sub-Saharan farming communities. In both modules, students are guided through a decision tree involving open-ended questions that combine physics with feasibility, such as energy output of humans, the distance to the river, and the area of the land to be irrigated. The activities embrace ambiguity, which is unavoidable in the real world. A course on technical innovation and entrepreneurship has also been developed and offered by the physics department to its own majors and others at LUM since 2016.

Technical Competencies Supporting Physics, Innovation, and Entrepreneurship

Led by Randall Tagg
University of Colorado Denver (CUD)

Prototyping requires integrating several technical competencies, including electronics, mechanical systems, sensors, actuators, optics, and computer-aided data acquisition and control. In some cases, vacuum systems, microwave systems, feedback control, and plasma generation are also needed. To introduce first-year physics majors to a basic range of competencies, the PIE initiative at CUD developed a two-semester sequence of applied physics labs. The formal lab work is augmented by informal opportunities to learn procedures,

such as soldering, CAD, and 3D printing. A “grand finale” experiment from the module appears in the accompanying photograph. Designed to measure the speed of a DC motor in response to changes in frictional torque, the experiment incorporates, among other things, Python code to run it, a LabJack computer data-acquisition interface, and a converted LED flashlight used as a strobe. CUD’s lab staff Devin Pace and Kris Bunker designed and built the apparatus.



Pop-Up Courses on Industry and Innovation

Led by Linda Barton
Rochester Institute of Technology (RIT)

At RIT we have experimented with what we call pop-up courses—short, informal workshops that introduce students to new topics in a low-pressure, casual atmosphere. Pop-up courses are typically self-contained, interactive, exploratory, and not highly scripted. At RIT, pop-ups have covered basic hands-on technical competencies such as electronics assembly, introductory metal working, and programming Arduinos (which was very popular, with student interest leading to additional activities on Linux installations and BASH scripting). We have also used pop-ups to explore career development topics, including résumé writing, job searching, elevator pitches, and networking (largely based on the Society of Physics Students Careers Toolbox). Whenever possible, we schedule career pop-ups to coincide with career fairs. Pop-up classes can

serve as a vehicle for faculty development of curricular modules that could later be integrated into more traditional courses. Alternatively, the classes can stand alone as a fun way to broaden the training of physics students beyond the usual canon of traditional problem sets on traditional topics. The pop-up format makes it easy to introduce innovation and entrepreneurial elements (or any other material of interest) into the physics curriculum.

Agile Project Management in Physics Design Projects

Led by Wouter Deconinck
William & Mary

At William & Mary we developed capstone design projects in which student teams of three to five physics seniors solve research and technology development problems. Faculty researchers or external partners provide the problems and their contexts. To avoid analysis paralysis, we use concepts drawn from the agile approach to managing software development—namely, sprints (short, iterative bursts of development), scrums (brief daily meetings to share progress reports), and kanban (bulletin boards to track progress). Teams are required to demonstrate an increasingly functional prototype after each three-week sprint. The team generates and prioritizes a list of tasks at the start of the sprint. Every second day the team gathers for a 10-minute stand-up meeting (the scrum) to review a task-tracking board (the kanban) led by one of the students who is the scrum master. Each sprint ends with a prototype demonstration to the product owner (the faculty member or external partner) and a retrospective session, in which the team reflects on collaboration and performance. Together, the scrums, demos, and retrospectives give students opportunities to practice and improve their oral communication skills. They also instill self-motivation and project ownership better than do our traditional individual senior research projects.

ity and content of the physics education. Indeed, the core of our work is to develop educational approaches that teach innovation and entrepreneurship while retaining the factors and features that make a physics education so valuable.

Baking PIE: The APS PIPELINE Network

Several activities have occurred in the past few years to help those interested in PIE. Among them was a conference held in 2014 at the American Center for Physics in College Park, Maryland, attended by faculty from more than 40 institutions. One

of the meeting’s outcomes was a set of recommendations for how the value of innovation and entrepreneurship education could best be communicated and disseminated to other institutions. Recommendations included holding sessions at society meetings, creating a newsletter for communication, and creating and disseminating approaches for implementing PIE education. Out of those recommendations came a road map for the next steps that ultimately became a project called the Pathways to Innovation & Physics Entrepreneurship: Launching Institutional Engagement (PIPELINE) Network.

Box 2. Faculty Views of PIE

Forty faculty members from seven institutions participated in a study that assessed their perceptions, awareness, and experiences with physics innovation and entrepreneurship (PIE). Many of the challenges, such as boosting the role of computation and increasing the use of research-based instructional strategies, are shared by other

efforts aimed at changing the way physics is taught. The commonality of challenges suggests that many effective ways developed to support those other initiatives could also work for PIE.

Sixteen faculty members whom we surveyed reported challenges in implementing PIE at their institutions. The following

Response	Are you aware of PIE?	Have you faced challenges implementing PIE?
Yes	53%	40%
Not sure	35%	20%
No	15%	40%

Meanwhile, activities focused on the career development of physics students have also taken place in the past few years. In 2014 APS and the American Association of Physics Teachers (AAPT) convened a joint task force on undergraduate physics programs (J-TUPP). Released in 2016, the task force's report, *Phys21: Preparing Physics Students for 21st-Century Careers*, identified the technical, communication, and workplace-relevant skills that physics students need besides expertise in physics.³ (The report is outlined in the article by Laurie McNeil and Paula Heron, PHYSICS TODAY, November 2017, page 38.)

PIE aligns perfectly with the recommendations of *Phys21*. As awareness of the report has spread within the physics education community, increasing numbers of physics faculty are beginning to consider incorporating PIE in their teaching.

In September 2016 APS launched the NSF-funded PIPELINE Network. The collaborative, three-year project unites the efforts of seven institutions (William & Mary, George Washington University, Loyola University Maryland, Rochester Institute of Technology (RIT), Worcester Polytechnic Institute, Wright State University, and University of Colorado Denver) to develop and disseminate PIE materials and to seed a nascent community of experienced PIE practitioners. PIPELINE is guided by educators who have already established successful innovation and entrepreneurship programs for physics students, including one of us (Arion), whose ScienceWorks entrepreneurship program at Carthage College launched in 1994; Ed Caner, who is with the physics entrepreneurship master's program at Case Western University; and Dan Ludwigsen at Kettering University. PIPELINE's work has also been guided by an advisory board of industrial physicists who have extensive experience as entrepreneurs and in the private sector.

A primary goal of PIPELINE has been the development and testing of several sets of curricular materials. Some of them are described in detail in box 1. The courses have received enthusiastic reviews from students who took them, and many additional student-driven projects have sprung from those initial activities. Some have caught cross-campus attention and created new opportunities for collaboration among departments and disciplines; many institutions value such opportunities.

Our second goal, increasing engagement of physics faculty in the PIE community, has been more challenging to achieve

themes, ranked in order of prevalence, emerged.

1. Lack of knowledge about nonacademic careers limited faculty's ability to develop and deliver PIE-related curricula.

2. Lack of recognition for faculty who integrate PIE and career-focused elements into their teaching reduced motivation.

3. Lack of interest among colleagues and, more broadly, their departments left PIE champions feeling isolated.

4. The physics major is already full, leaving little room for new topics, such as PIE.

5. Resources were lacking, including connections to alumni who work in the private sector, time and funding to develop and implement PIE, and curricular materials.

and measure, despite our monthly PIE newsletter, our talks at numerous invited sessions at APS and AAPT meetings, and the articles we've written for APS publications. In 2017 a general survey went out to members of the APS Forum on Education. Of the 68 who responded, at least half indicated that they would take advantage of resources that would help them implement PIE. Yet the number of physics educators at PIE-focused workshops and sessions at annual APS meetings remains dwarfed by the number of students and early-career physicists who see the value of the entrepreneurial mindset and the broader application of their physics training.

Why educators seem reticent to fully engage is revealed by a third goal of PIPELINE: an assessment and evaluation process that looked at the attitudes toward PIE of both faculty and students. As detailed in box 2, many physics faculty seem to recognize the general value of PIE and are interested in learning more. (The findings in boxes 2–4 come from research by Benjamin Zwickl of RIT and Anne Leak of High Point University.) Yet obstacles to implementation remain, including a lack of familiarity with PIE concepts, lack of recognition and support for such activities at the institutional level, and the perception that physics content will be lost by incorporating PIE into the curriculum.

Many faculty members don't realize that they don't have to teach both physics and PIE themselves, so it's not a zero-sum game when it comes to their time. Students can gain PIE skills through a variety of on- and off-campus experiences. The physics curriculum can still address all of the core topics, skills, and abilities that make physicists so valuable while also preparing students for careers in industry.

That principle of combining core physics with entrepreneurship and innovation is exemplified by a module developed at Loyola University Maryland, and based on Hyperloop, the high-speed transportation system being explored by Tesla and SpaceX. Hyperloop envisions sending trains of pods containing people or freight through airless tubes. Instead of teaching kinematics by having students solve an arbitrary projectile motion problem, the module guides students through problems of increasing complexity associated with the feasibility of operating a train moving at 730 km/h in an evacuated tunnel. As the students tackle the problems, they have opportunities to exercise their creativity by devising innovative ways to ensure that design or

Box 3. Student Views of PIE

The seven essential aspects of PIE label the columns of the chart on the right. Students learn, think they learn, or fail to learn about them through various channels (rows) and at different rates (numbers), as the chart and quotations illustrate.

"Sometimes design skills may be needed in a lab and will most likely be needed in research. However, you usually don't learn too much in the actual physics class."

"I am a leader on my volleyball team at school, so I think I have learned team efficiency strategies from there and have incorporated them into my academic work."

"I have learned a lot about technology during my research. It has helped me specifically understand how computer programming works."

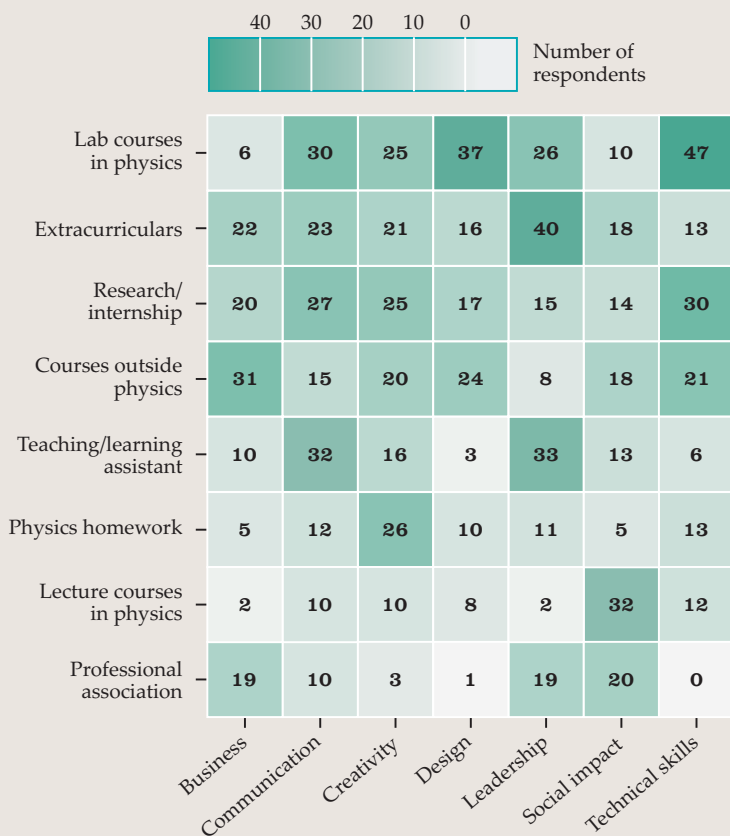
"I haven't learned any business skills in my physics classes. The only place I have absorbed business skills is from my financial accounting class."

"Being a TA allows me to have time to thoroughly explain my reasoning behind physics topics to others with little experience."

"Homework has provided me the most opportunity for creativity in physics because there are usually multiple ways to approach a problem. We have to figure out which approach is best."

"The only place where I have heard about the impacts of physics on society is in my science, technology, and values class, where we have been learning about the making of atomic bombs."

"After attending meetings for both SPS and Women in Science, I get a very clear picture of what my life might be like after my physics degree."



physics considerations do not impair the technology's desirability. What's more, the module deliberately asks open-ended questions and leaves crucial quantities undefined. For example, students are to assume that the train accelerates at a "comfortable" rather than specified rate. The tactic familiarizes students with ambiguity and encourages them to make reasonable, well-informed estimates. The ability to confidently move beyond the boundaries of what is known and make good guesses is a characteristic of physicists. Students who take the module acquire the essential mindset of a physicist while solving a real-world problem, and they do so at the start of their physics education.

Students also harbor misconceptions about PIE. As boxes 3 and 4 detail, our research revealed that students' perceptions differ from those of experts. In particular, students did not believe that some aspects of innovation and entrepreneurship were—or even should be—taught within physics. They did not gain an understanding of the discipline's benefits to society. They maintained a belief that the disciplinary boundaries between, for example, physics, engineering, and business are real and that their physics education doesn't require understanding design and learning cross-disciplinary topics.

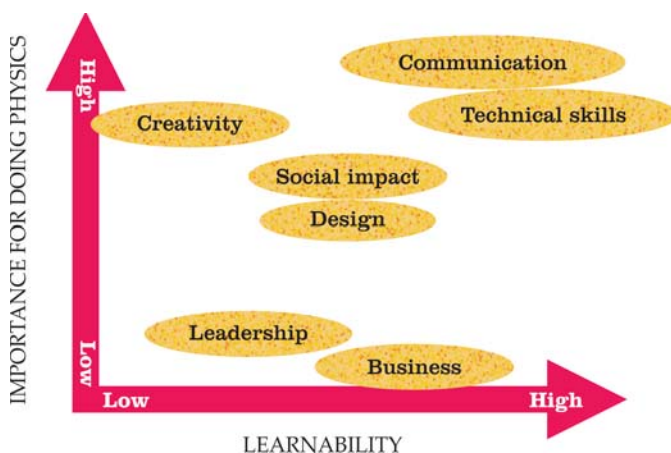
That last revelation is especially unfortunate because cross-disciplinary skills are essential even for careers in fundamental physics research. More importantly, when most students go out to work in the private sector, they will be working on interdisciplinary teams. Part of their value as generalists is to be able to speak lots of different disciplinary "languages." Their perception that they should let arbitrary boundaries define what they can and can't do diminishes that value.

In addition to attitudinal roadblocks among faculty and stu-

dents, there is also a dearth of tested, effective PIE materials that can be used by practitioners with different experience levels. Also lacking among physics faculty are knowledge of and comfort with teaching PIE concepts. Encouragingly, 89% of the respondents to the APS Forum on Education survey said that they would take advantage of an online platform for sharing and developing PIE curricula.

How to make this happen

To reiterate: PIPELINE aims to prepare students for 21st-century career options and to make them more effective at solving the



IMPORTANCE AND LEARNABILITY of seven aspects of PIE as perceived by students.

Box 4. How Experts and Students Define the Seven Aspects of PIE

I&E aspects	Expert definitions	Student definitions
Business	Goal-driven, client-oriented, consideration of costs and systems	Consideration of cost, awareness of audience, social interactions important
Communication	Teamwork, audience and purpose, working with clients, asking questions, documentation, presentations	Teamwork, explaining physics clearly and concisely, focused on oral communication more than written communication
Creativity	Novel ideas and solutions, innovation in products and processes	Essential for solving problems, especially complex ones with unclear solutions
Design	Awareness of end user and purpose, modeling and software, systems thinking	Creating experiments and computational models, using design software
Leadership	Project or team management, initiative, organizational mindset	Collaboration with peers, leading group work, teaching physics to others
Social impact	Considering impact on people and communities, making positive change	Negative impacts of physics, advancing science through physics discoveries, relating physics to personal experiences
Technical skills	Programming, hardware, specialized tools/equipment, hands-on making	Programming, software, lab equipment

problems of today and tomorrow. To accomplish that vision, it's important to help physics faculty understand the value of teaching PIE, help physics faculty who are interested do so effectively, and help physics students understand that the skills, knowledge, and mindset they gain through PIE will bring them closer to realizing their dreams.

To expand the community of practice to include more faculty (and departments) that are invested in adopting PIE, we first want to create mechanisms that facilitate the successful implementation of existing PIE curricula. Physics faculty members who are interested in teaching PIE should have access to resources that will enable them to at least experiment even if they aren't experienced practitioners.

We also want to create scaffolding for physics faculty members who are currently implementing and developing new approaches to PIE. By using the scaffolding, the developers of PIE materials can share what they have created with others, who in turn can build approaches that work in their particular landscape of resources and barriers. When the initially "PIE-curious" begin to feel comfortable creating new approaches and mentoring the next rounds of adopters, we will see our promotional efforts turn a corner toward a self-sustained and self-led community. Eventually, what we believe is a long-overdue evolution in physics pedagogy will not only help physics graduates get jobs but will also inspire and empower them to make positive changes in the world.

All PIE approaches developed under PIPELINE, including the ones mentioned in box 1, can be found on our website (go.aps.org/innovation). Educators are heartily invited to use and adapt the materials and to submit approaches that they de-

velop. Through early 2020, APS will be hosting a series of webinars that introduce each of the existing PIE approaches and provide advice on implementation. The webinars will include a Q&A session during the live broadcast, and the recording of the presentation and discussion will be available with the source material. You can sign up to receive notifications of the broadcasts by subscribing to *APS PIE News*, a monthly newsletter featuring newly developed PIE curricular approaches, fresh opportunities to learn more or get involved in PIE, and resources available through APS and other organizations, such as the American Society for Engineering Education and VentureWell. To join the newsletter mailing list, visit the PIE website. Lastly, we have compiled a PIE speakers' list, which is also available on the PIE website. Here you can find people who can describe the materials they have developed, provide advice on your efforts, and help you build institutional support.

Building a successful 21st-century workforce, maintaining the relevance of the study of physics, and adapting education to the shifting demographics and pressures on institutions are keys to the success of physics as a discipline and the future of higher education. We hope that you will join us in these efforts.

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