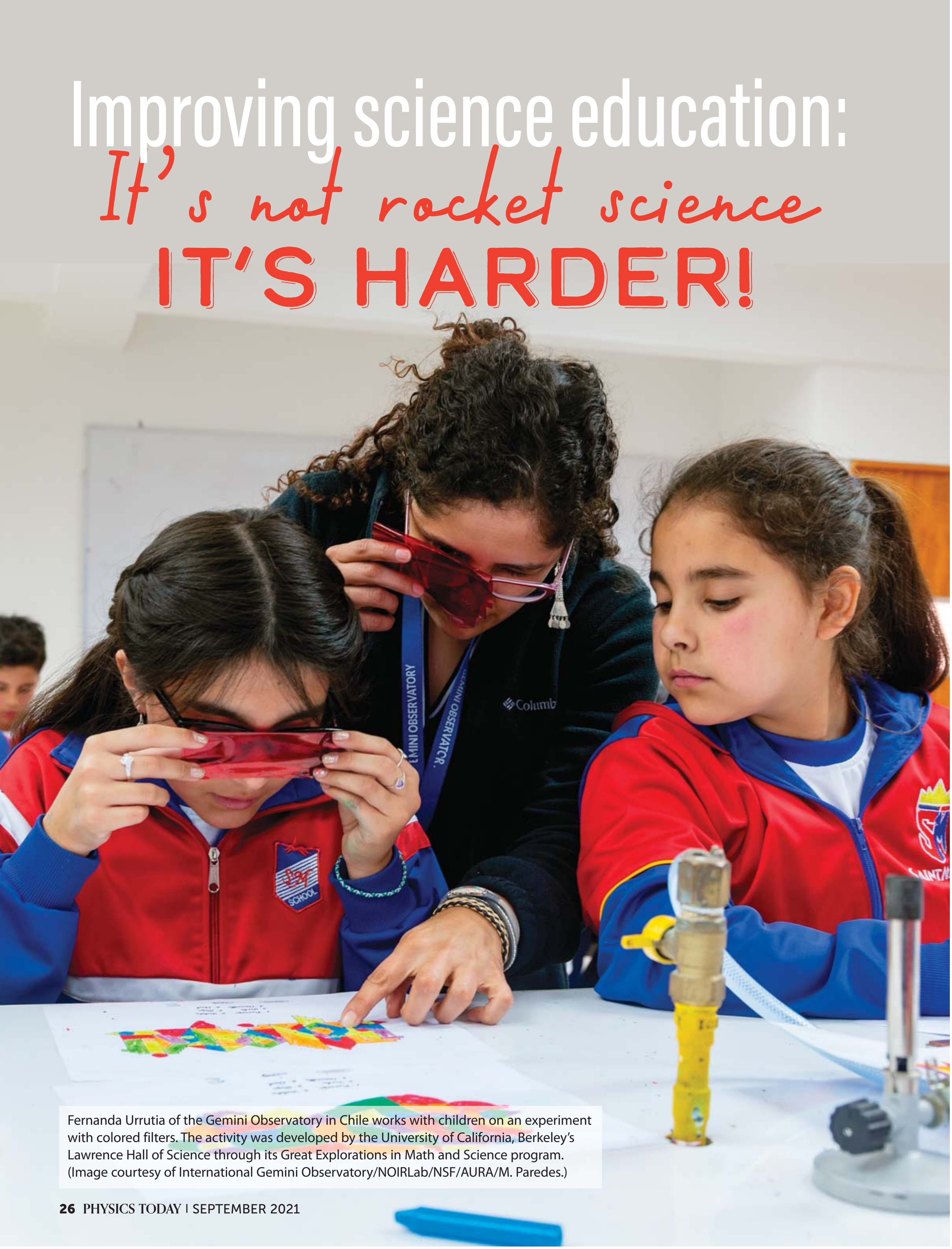
Improving science education:
It's not rocket science
IT'S HARDER!



Fernanda Urrutia of the Gemini Observatory in Chile works with children on an experiment with colored filters. The activity was developed by the University of California, Berkeley's Lawrence Hall of Science through its Great Explorations in Math and Science program. (Image courtesy of International Gemini Observatory/NOIRLab/NSF/AURA/M. Paredes.)

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Stephen M. Pompea and Pedro Russo

Scientists can help by partnering with museums, out-of-school programs, schools, organizations that develop instructional materials, or other educational projects.

Our subtitle paraphrases a frequent statement from George "Pinky" Nelson, an astronomy researcher who spent 11 years as a NASA astronaut and flew on three space missions, including the first one after the *Challenger* accident. In the decades after his stint at NASA, he expanded his career and straddled the fields of science research, engineering, and science education—he served, among other roles, as a professor of physics at Western Washington University and as director of the American Association for the Advancement of Science's Project 2061, a long-term R&D initiative focused on improving science education. Nelson's informed perspective highlights the difficulty of enhancing the science education system.[1]

Efforts to improve science literacy and science education have faced many challenges in recent decades. In the US, for example, the No Child Left Behind Act of 2001 emphasized a high-stakes testing program that eroded teacher and school autonomy and thus weakened and stalled long overdue changes in science education practices. That trend may change as physicists increasingly recognize the importance and value of their own and their organizations' engagement in educational activities. By participating, they will gain personal satisfaction and strengthen their organizations' bonds to their communities. What's more, those activities can fulfill the "broader impacts" criteria required by NSF and other funders or can meet institutional obligations to disseminate knowledge of scientific methods and results.

In this article we highlight some trends that are encouraging physicists to join ongoing efforts to improve science teaching and learning worldwide. Although not new, those trends are again gaining attention and interest from scientists and their organizations. The efforts center on a broad systems-based approach that recognizes the complexity of the science education ecosystem. With a foundation of the best research-based pedagogies, physicists can step into partnership roles in schools, outside-of-school programs, international events, and other activities designed to improve science literacy.

Using best practices

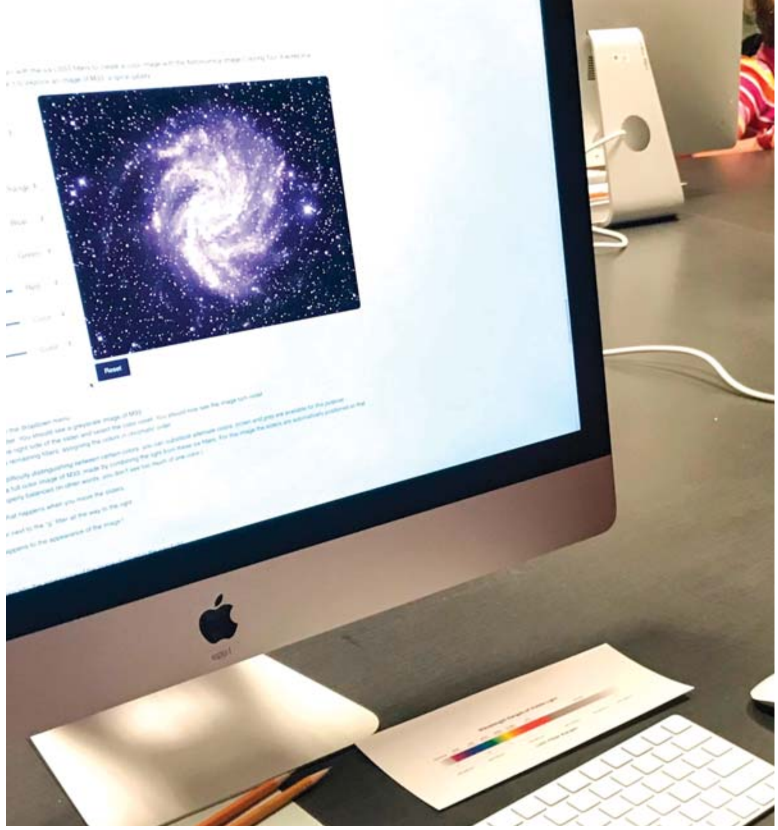
Our knowledge of the challenges of educational transformation comes from decades of experience designing, implementing, and evaluating innovative science education projects. We have collaborated with new and experienced teachers, museum educators, educational researchers, and educational development teams to reach audiences from preschool children to older adults. We have also worked with diverse science, engineering, and education professional societies and with governments and nongovernmental organizations worldwide. In our work with scientists at national laboratories, universities, and industrial research facilities, we have learned many lessons on how we can be more effective in our educational efforts and have applied them to our work.

From our experience working in the education arena, we know that physicists have had the most success and enjoyment when they have been well prepared about their audience and its needs. Many scientists are unfamiliar with the best practices for teaching and learning at preschools, primary and secondary schools, afterschool clubs, and museums. Fortunately, high-quality free resources are available that summarize the extensive research on learning in diverse settings.[2]

To streamline the process for scientists who are getting involved for the first time or who want to increase their level of involvement, we recently completed a review of the research on best practices for supporting and interacting with the part of the science education ecosystem that encompasses preschool to high school learners.[3] Although our review is specific to astronomy, most of the suggestions apply to all fields of science and engineering education. We highlight throughout this article a few of those best practices most useful for scientists.

Starting young

Working with undergraduate and graduate students is easier and more familiar to many scientists than working with younger



students. Older students already have mathematical and scientific foundations to build on and have opted into science classes. Teaching them has been compared to shooting an arrow and then placing the target at the landing site just before the arrow hits. Hitting the bullseye is still satisfying but raises the question of how much influence a teacher has on an older student. Introducing science to children at younger ages is challenging but can greatly expand their science perspective during their highly formative and less predictable early development.

In the early 1960s, Jerome Bruner at Harvard University initiated many of the science education reform efforts of current importance. His focus was on early learning and a so-called spiral curriculum, wherein subjects are explored in more detail each year rather than being "saved" for a specific age range—for example, chemistry in 10th grade and physics in 11th grade. Bruner strongly believed that any science concept can be adapted for any age level. For the youngest students, actively engaging with science activities and demonstrations will be more effective than being given verbal or mathematical explanations, which may work for older students. Bruner pointed out that people learn to ride a bike by doing it, not by looking at a picture book or an instruction sheet.

Robert Karplus, in his mid-1960s work at the University of California, Berkeley's Lawrence Hall of Science, also offered a method to improve the elementary school science curriculum. He left his career in theoretical quantum electrodynamics research because he believed that working with younger learners would be as challenging and rewarding as his university research and teaching. Karplus developed and championed a learning-cycle model that has proven effective for learners of all ages. His cycle posited that learning happened in three phases—exploration, invention, and discovery—that could be cycled through repeatedly. His main legacy is the emphasis on hands-on experiences over textbook-centered learning. Karplus's learning-cycle model, which has been modified by many others since, reflects a deep understanding of the scientific investigation process and allows for rigorous student engagement in science exploration, learning, and applications.[4]

Elementary school teachers typically focus on imparting basic foundational skills in reading, writing, and mathematics. Although they understand the best teaching approaches, including those derived from Bruner and Karplus, applying their skills to teaching science is difficult because of pressure to concentrate on other subject areas. Many elementary school teachers also lack confidence in their knowledge of science topics and how to effectively integrate science and their core subjects.

Scientists can work with teachers to overcome those difficulties by engaging with such teacher–scientist partnerships as the NSF Graduate Fellows in K–12 Education and the Astronomical Society of the Pacific's Family ASTRO and Project ASTRO programs.[5] Scientists know the science, and teachers know how children learn. Both can gain from a deeper understanding of how younger students learn science. Guided by educators aware of students' science misconceptions and naive theories, a class can explore science concepts more successfully. And for scientists, working with elementary teachers is highly rewarding and constructive.

Roles in schools

Scientists have more to offer schools than classroom presentations and demonstrations in person or by video. Traditionally, scientists have taken on school roles based on their assessments of what a class or school lacks, often from their own childhood experiences or from short-term involvement in their child's school. A better approach is for scientists to work with teachers and find the best ways to address the most pressing classroom concerns. The scientists are then responsive to and respectful of the needs of the teaching professionals working every day in the educational arena.

Science teachers often express a need for more training in online teaching methods, access to high-quality interactive-learning materials, and more information about current science discoveries and techniques. They also are interested in having a scientist on call who can explain concepts and terms, help them find appropriate activities and demonstrations, and support and encourage them as part of their professional support system. Most elementary- and secondary-level science teachers say they have an inadequate educational background to effectively teach the physical sciences. That need for more professional preparation and support has been persistent for decades; from our perspective, it seems to become more acute every decade.

One way to meet teachers' needs is to become what's known as a science ambassador. In that role, scientists serve as a liaison between the science and education communities. They help teachers find educational materials and equipment and connect them to a university or research community. An ambassador must understand how the formal education system works: how educators are trained, what demands they deal with, and how students learn science concepts at each age level.[6] Professional societies, such as the American Astronomical Society, offer ambassador training at conferences.

Active science in the classroom

Scientists are often surprised to discover that many school science classes devote little or no time to students actually doing science. We, too, have found that it is increasingly rare for

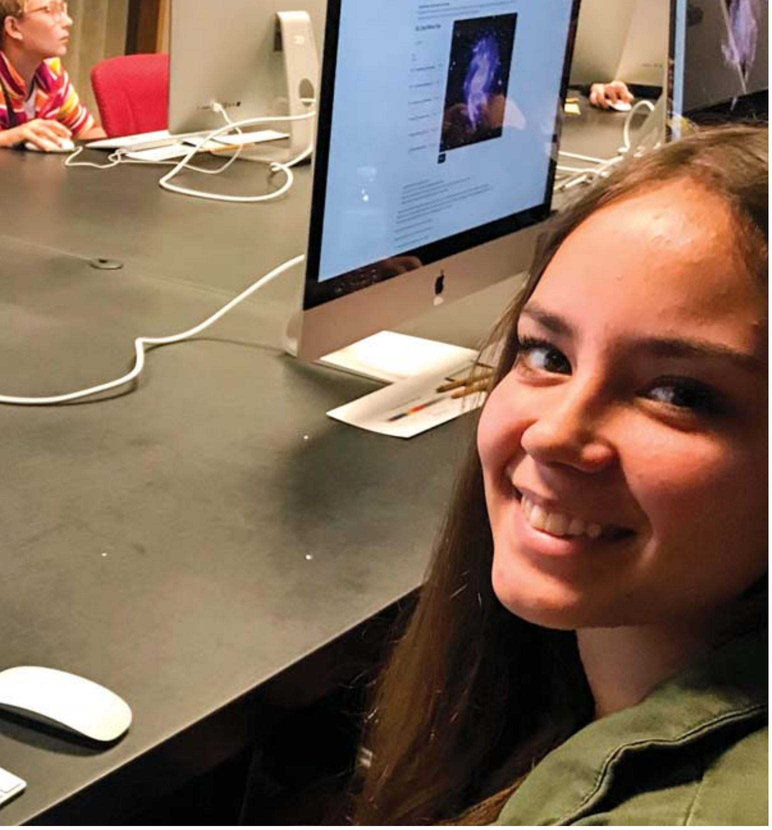


FIGURE 1. COMPUTER-BASED TOOLS are available at the Teen Astronomy Café at the Vera C. Rubin Observatory in Tucson, Arizona. Students use them for analyzing large data sets. The café also offers science talks and informal discussions with graduate students and postdocs, and coffee and food are available. Because of the COVID-19 pandemic, the café is now freely available online at www.teenastronomycafe.org. (Image courtesy of NOIRLab/NSF/AURA.)

elementary-age learners to perform even simple physical science experiments, despite those activities' proven effectiveness in getting them excited about the subject.[7] Instead, classes at all levels often consist of learning science vocabulary, memorizing the scientific method, and reading or talking about science principles or laws or about scientists.

In effect, classes emphasize science preparation calisthenics at the expense of allowing students to play the science game. The result is science classes that are boring and pedantic, a detrimental combination. As Robert Yager, former head of both the National Association for Research in Science Teaching and the National Science Teaching Association, pointed out in a 1988 essay, doing science is immensely more interesting:

> Unfortunately, however, our students rarely get to play—rarely get to do real science, to investigate a problem that they have identified, to formulate possible explanations, to devise tests for individual explanations. Instead, school science means 13 years of learning the rules of the game, practicing verification-type labs, learning the accepted explanations developed by others, and the special vocabulary and the procedures others have devised and used.[8]

In our experience, gifted students are often the ones most frustrated by not having a chance to participate in science questioning and exploring. One highly gifted student we know almost dropped out of junior high school after being labeled by his science teacher as difficult and disruptive. What had he done? He had challenged the teacher by asking for evidence that Earth goes around the Sun. Scientists welcome and applaud such questions and challenges rather than being threatened by them. That student is now a distinguished engineer at IBM. Science participation, not dogmatic memorization, powers science enthusiasm.

Free-choice education

When choosing science education roles, physicists often gravitate toward schools and classrooms. But other opportunities are available in afterschool and out-of-school programs. Those informal, free-choice settings include afterschool clubs, natural history and science museums, planetariums, libraries, hands-on science and technology centers, and visitor centers at research facilities. Other options are street fairs, county and tribal fairs, community events, summer camps, science cafés, science festivals, talks in restaurants and pubs, and any other place that gathers a potentially science-interested audience.[9]

Examples of the many available activities for scientists at those venues include helping design a museum exhibit, creating a science program for a children's discovery center, and giving a talk at a local library.[10] Scientists are especially effective in informal settings, such as pub and restaurant science nights, teen science cafés, and science festivals, when they encourage their audience to actively participate.[11] (See figures 1 and 2 for examples of two such events.)

Making a talk shorter and less formal and leaving significant time for discussion, debate, and wide-ranging questions can improve audience interest, engagement, and satisfaction. Similar to other fields, the informal education field has a strong research basis behind its pedagogy. It is specialized and sophisticated, and it offers diverse and expanding roles for informal education professionals.[12]

Building science capital

Many innovative science education programs are built on a concept called science capital, a term from the 2013 influential UK science education policy report *ASPIRES: Young People's Science and Career Aspirations, Age 10–14*. Science capital refers to the sum of all science-related knowledge, attitudes, experiences, and resources that individuals build up, including the science they know and learn, what they think about science, and their daily engagement with science and science-interested people. A capital-based perspective of the educational ecosystem encourages partnerships that offer children the opportunity to learn about STEM (science, technology, engineering, and math) in school and other settings and that encourage systemic change to create a support system for learners.[13]

Creative approaches to reach or serve new communities have been successfully implemented worldwide, often with scientists as key team members. For example, scientists have contributed to programs that encourage design and visual thinking in science. Such programs—called STEAM for their combination of the STEM fields and art—can inspire children with artistic interests and visual thinking skills to pursue science and technology-related careers.

Laura Carsten Conner, an associate professor of science education at the University of Alaska Fairbanks, and her collaborators have studied how girls view science and the value of art–science connections in building their science identities. Her research formed the basis of the programs Colors of Nature and Fostering STEAM, which combine art and science and were developed by a team of physical and biological scientists, visual artists, informal science educators, and educational researchers. The programs include science cafés that host interactive events with scientists, training for education professionals on integrating art and science into lessons about nature's colors, and two-week summer academies for girls to explore color with scientific tools such as spectrometers and light and scanning electron microscopes (see figure 3).

Carsten Conner's projects have demonstrated the importance and value of building science capital as a core approach to innovative science education. Art–science connections can reach new audiences and offer an encouraging environment for students to start building up that capital.[14]

International and global programs

Many scientists have told us that singular experiences, such as looking through a kaleidoscope, seeing the Moon magnified, observing with an IR camera, playing with a gravity well, or watching the magnetic levitation of a superconductor, were life-altering events. Many want to know how they can share those powerful experiences.

One way scientists have connected with others has been by taking part in ambitious worldwide educational projects, many centered around United Nations–initiated international years that publicize a particular science or the anniversary of an important scientific event. Some examples are the International Year of Astronomy 2009 (IYA2009) to celebrate the 400th anniversary of Galileo Galilei using his astronomical telescope; the International Year of Light and Light-Based Technologies 2015 (IYL2015); the 100th anniversary of the International Astronomical Union (IAU100), which took place in 2019; and the International Year of Sound 2020–2021 (see the December 2020 issue of PHYSICS TODAY). Those international-year designations are ubiquitous and can motivate scientists to create projects that reach new audiences. Although the time-limited and somewhat ad hoc nature of the events could be a detriment, in practice the novelty and urgency inspire ambitious new ideas and approaches.

International projects are largely led by scientist volunteers who rely on the sponsoring organizations to encourage the participation of their scientist members. For example, the IYL2015 team comprised scientists and engineers from the Optical Society, SPIE, the American Physical Society, the European Physical Society, and other partners outside the US.

To succeed educationally, an international-year program needs strong leadership and planning. Securing the official worldwide designations often requires three to five years of advance planning. Each project in the program will be more successful if it has a bold, focused goal and a diverse team of scientists and educators to plan and implement it.

For example, for the well-received IAU100, led by Ewine van Dishoeck of Leiden University, scientists partnered with educators to create many worldwide education projects. One of them, the Einstein Schools Programme, offered online resources for students to learn about the varied effects of gravity and was adopted by more than 200 schools worldwide (see figure 4).

FIGURE 2. COMMUNITY-BASED educational events such as Astronomy Day or National Astronomy Week are effective ways to bring science activities to wide audiences. During this 2019 activity at the Prince Kuhio Plaza shopping mall in Hilo, Hawaii, a staff member from the Gemini Observatory investigates colored filters with a student. At the annual event, the observatory connects to the community and learns more about its educational needs. (Image courtesy of International Gemini Observatory/NOIRLab/NSF/AURA/J. Pollard.)

Another particularly successful set of projects[15] was developed for IYA2009. From Earth to the Universe created exhibitions of astronomical images from various telescopes that were translated into 40 languages and used in 70 countries and a thousand locations, including parks, libraries, subway stations, and airports. Overall, 10 million people saw them. The Galileo Teacher Training Program, which was initiated with volunteer help in 75 countries, created the largest international network for astronomy teacher training workshops.

Also a product of IYA2009, the Galileoscope student telescope kit[16] was created by three US scientists supported by a team of individuals and organizations, including the American Astronomical Society. The team lamented the lack of high-quality but inexpensive telescopes for kids and decided to fix the problem. With some institutional support and partnering but no initial funding, they designed, manufactured, and distributed a quarter of a million new high-quality telescope kits with accompanying educational materials to 110 countries. The Galileoscope is still in production, and its educational materials are free and widely available.

In our experience, scientists bring great value to such projects because of their willingness to share their intense passion about science.

Scientist–educator hybrids

As scientist–educator hybrids ourselves, we've noticed that more scientists each year are choosing to pursue and integrate both roles into their careers. The share that each person gives each role varies with their interests, skills, and career stage. Many scientists have gone beyond educational volunteering and have become full-time education and community engagement professionals. Others enjoy helping, designing, or implementing new programs as part of education and community engagement teams with the support of their university, research lab, medical center, or company.

Scientists on educational development teams fill an important and perhaps unique role by modeling educational materials and projects after the process of scientific investigation. For example, in 1992 Craig Blurton of the NASA Classroom of the Future in West Virginia directed and supervised many bleeding-edge educational software projects in the fields of astronomy, planetary science, biology, and environmental science. He brought scientists from across the country who shared a passion for both research and education to work with his educational researchers and multimedia developers. Together they created realistic and immersive simulations that allowed students to do science as part of teams exploring cutting-edge science problems.

Among the results were the computer programs *Astronomy Village: Investigating the Universe*, geared to high school students and supported by NASA, and *Astronomy Village: Investigating the Solar System*, geared to middle school students and supported by NSF. The educational packages won many awards, including Best Microcomputer Software of the Year from *Technology and Learning* magazine. Students at the virtual Astronomy Village, shown in figure 5, work in teams on research projects with simulated instruments, space probes, and ground-based telescopes. They do laboratory and thought

FIGURE 3. ART-INCLINED STUDENTS at the Colors of Nature program use microscopes, cameras, and spectrometers to learn about fluorescence, animal vision, polarization, the spectral properties of pigments, light interference, and structural color. The program, which supports students, families, and educators interested in exploring the connections between art and science, hosted multiple summer academies for girls in Tucson, Arizona (shown here), and Fairbanks, Alaska. (Image courtesy of NOIRLab/NSF/AURA/S. Pompea.)

FIGURE 4. KIP THORNE (center) in 2019 meets the student team from Chile's University of La Serena and its NOIRLab project leaders who performed observations at the Cerro Tololo Inter-American Observatory during that July's total solar eclipse. The measurements re-created the famous century-old results that confirmed the bending of light predicted by general relativity. The project was part of the Einstein Schools Programme for the 100th anniversary of the International Astronomical Union, which facilitated creative projects worldwide for students to explore the role of gravity in astronomy. (Image courtesy of NOIRLab/CTIO/NSF/AURA/P. Marenfeld.)

experiments and use image processing to analyze real images and data from NASA, NSF, and NOAA. At the end they announce their results at a mock press conference and answer probing questions.

Those two programs capture the essence of collaborative science research and immerse students in authentic, cutting-edge topics, such as extrasolar planets, Earth-crossing objects, the search for life in our solar system, and supernovae searches. The packages were also among the first instructional materials for secondary school students that used the internet (Netscape 2.0 for the first Astronomy Village program!), email messages, and sophisticated image processing.

Another group of scientists and educators was led by astronomer Isabel Hawkins, who was director of the Center for Science Education at the Space Sciences Laboratory, University of California, Berkeley, from 1997 to 2008. They developed innovative instructional materials for the Great Explorations in Math and Science project. Their resulting nationally tested astronomy teacher guides draw from research-based teaching methods, including those of Karplus, and are easy to use even for teachers with limited math or science backgrounds.

Many hybrid scientist–educator teams have developed high-quality instructional materials that capture the essence of scientific exploration. Physicists interested in creating instructional materials can join similar development teams that have a track record of addressing the current needs of teachers and students.

Taking a long-term perspective

Physicists can appreciate the impact of forces acting over long periods of time. Addressing the persistent and seemingly intractable problems in the science education ecosystem requires an enduring effort and continued systemic change. Despite many notable educational achievements and innovations, in our opinion overall progress in science education has been erratic in the US and most other countries.

The quality of science education at all levels still varies widely. The fragmentation of US cities into multiple school districts and public, charter, and private schools all but guarantees inequities in resources, teaching, and learning. For most students, their postal address or ZIP code remains the best predictor of the short- and long-term educational achievements available to them.

Teachers lack access to high-quality instructional materials and training on how to use them. Labs for active learning and computer-based activities often fall into disrepair and disuse. Successful professional development programs for science teachers fade over time because of a lack of funding. New programs and organizations work to address those issues but make only small dents before they lose momentum or funding.

Research organizations that want to help improve education often end up collaborating with their local advantaged suburban schools rather than with needier schools that would benefit more from a partnership. Scientists and organizations can also fall into the trap of choosing projects that make them look good rather than have more educational merit. The more difficult task of establishing educational partnerships with di-

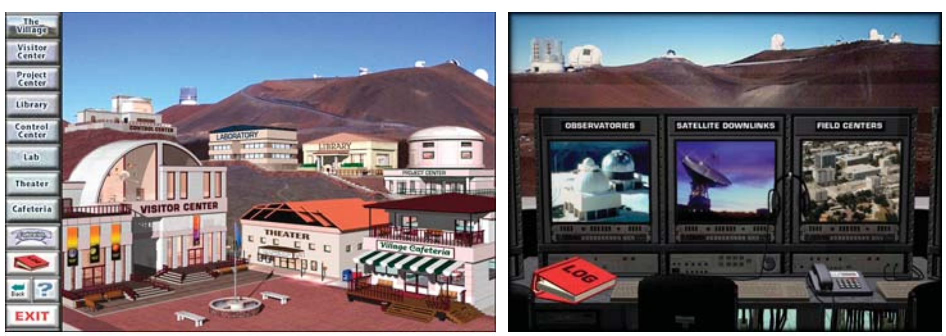


FIGURE 5. COMPUTER PROGRAMS let students simulate research in the planetary sciences with data from ground and space-based telescopes and interplanetary probes. In *Astronomy Village: Investigating the Solar System*, middle school students explore possible habitats for life throughout the solar system. They navigate from the home screen (left) to a simulated telescope with control panel (right), a virtual lab with instructions for on- and off-computer experiments, a simulated press conference where students answer probing questions, and more. The program uses research-based pedagogy merged with the typical research process, which includes ill-defined science problems that have no obvious right answers. (Image courtesy of NSF/Classroom of the Future, Wheeling Jesuit University.)

verse communities is replaced with the simpler short-term task that can generate good publicity.

The formal and informal science education systems need longer-term commitments from scientists and their organizations. In turn, those organizations must value, reward, and support the efforts of individual scientists. Neglected communities also require additional exploration, dialog, and time to develop an authentic partnership with a research organization and have their needs understood.

Next steps

Many scientists want to help improve the science education ecosystem. But buying magnets for a teacher is easy; training a new group of teachers each year about magnetism is much harder. The easy fixes have a limited effect. If you want to get involved, you will first need additional knowledge and experience to effectively improve science education locally, regionally, nationally, or internationally.

The investment that you make to understand the needs of your local community's educational system will provide a large return for you and the community. Partnering with educational institutions to pursue productive and efficient action together is also critical to help you avoid the frustration that occurs when you work in isolation.

So how can you start? Talk with a teacher or a youth club leader in an economically challenged area near you and partner with them long-term to meet their needs. Encourage your organization to devote its resources to address the broader needs of students and educators in struggling local communities. Answer this summons to service, and work together.

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