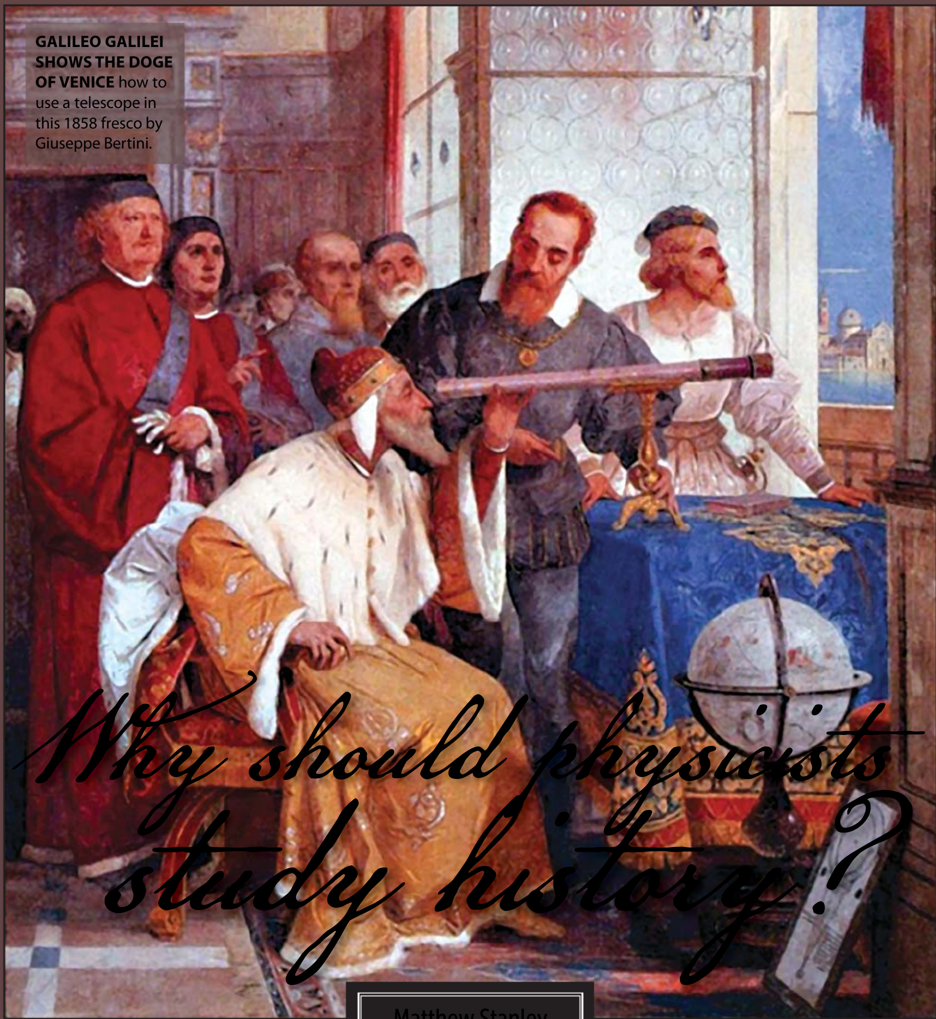

GALILEO GALILEI SHOWS THE DOGE OF VENICE how to use a telescope in this 1858 fresco by Giuseppe Bertini.

Why should physicists study history?

Matthew Stanley

Just as physics is not a list of facts about the world, history is not a list of names and dates. It is a way of thinking that can be powerful and illuminating.

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Some things about physics aren't well covered in a physics education. Those are the messy, rough edges that make everything difficult: dealing with people, singly or in groups; misunderstandings; rivals and even allies who won't fall in line. Physicists often do not see such issues as contributing to science itself. But social interactions really do influence what scientists produce. Often physicists learn that lesson the hard way. Instead, they could equip themselves for the actual collaborative world, not the idealized solitary one that has never existed.

History can help. An entire academic discipline—history of science—studies the rough edges. We historians of science see ourselves as illustrating the power of stories. How a community tells its history changes the way it thinks about itself. A historical perspective on science can help physicists understand what is going on when they practice their craft, and it provides numerous tools that are useful for physicists themselves.

Physics is a social endeavor

Research is done by people. And people have likes and dislikes, egos and prejudices. Physicists, like everyone else, get attached to their favorite ideas and hang on to them perhaps long after they should let them go. A classic case is the electromagnetic ether, an immensely fruitful concept that dominated physics for most of the 19th century. Even as it became clear that ether theory was causing more problems than it solved, physicists continued to use it as a central explanatory tool—even for many years after Einstein's 1905 theory of special relativity declared it superfluous. The history of physics is littered with beautiful theories that commanded great loyalty.

People come from places too, and physicists want to protect their homes as much as anyone else. It is easy to forget that 100 years ago during World War I, British scientists refused to talk to their German colleagues on the other side of the trenches. Even after the end of the fighting, Germans and their wartime allies were officially forbidden from joining international scientific organizations. During World War II, the specter of an atomic bomb in the hands of Adolf Hitler terrified Allied physicists into opening the Pandora's box of nuclear weapons. Many of the scientists involved bemoaned their actions afterward, but war and nationalism make for a potent impetus.

Those incidents are not exceptions. Physicists are not disinterested figures without political views, philosophical preferences, and personal feelings. The history of science can help dismantle the myth of the purely rational genius living outside the everyday world. It makes physics more human.

And a more human physics is a good thing. For starters, it makes physics more accessible, particularly for students. Many promising students drop out of the sciences because the material seems disembodied and disconnected from their lives. Science education researchers have found that those lost students "hungered—all of them—for information about *how* the various methods they were learning had come to be, *why* physicists and chemists understand nature the way they do, and *what* were the *connections* between what they were learning and the larger world."[1] Students can potentially lose the wonder and curiosity that drew them to science in the first place. Historical narratives naturally raise conceptual, philosophical, political, ethical, or social questions that show the importance of physics for the students' own lives. A field in which people are acknowledged as people is much more appealing than one in which they are just calculating machines.

Understanding the human side of physics will also better prepare students for what physicists actually do. Physicists work in groups. They need to talk. Physics is a social endeavor. Ideas and experimental equipment are exchanged constantly. In the early days of general relativity, it was extremely difficult to become proficient in the theory without direct contact with Albert Einstein or his inner circle.[2] And since the Great War was raging, few physicists could obtain that contact. General relativity became widely known only after Willem de Sitter, in the neutral Netherlands and in personal contact with Einstein, passed his relativistic skills on to Arthur Eddington in the UK. Fortunately, Eddington was a Quaker pacifist and one of the few British scientists willing to look at a German theory.[3] Physics works only when people talk to each other, and communication is not always easy.

Physics isn't obvious

Everything seems obvious in retrospect. Textbooks present experimental results as being self-evident and theories as needing at most a few pages of math to be proven true. But crystal-clear expositions conceal the enormous amount of work and confusion that goes into reaching scientific conclusions. The history of physics can remind us how difficult it is to justify ideas—from heliocentrism to atomic theory—that now seem so obvious.

Complexity, not simplicity, has ruled the practice of science.

Every discovery has come out of a messy mix of people, ideas, accidents, and arguments. Generally it takes a great deal of effort to understand what an observation or theory means. The Millikan oil drop experiment, for example, appears in textbooks as a model of clear experimental design and immediately persuasive theoretical interpretation. However, even a quick look at Robert Millikan's lab notebooks shows how immensely difficult it was for him to make his experiment work. (Figure 1 shows a sample notebook page.)

Nature rarely gives a straight answer. So researchers in science sometimes follow blind paths and usually need trial and error and second guessing. Once a robust result has been achieved, scientists tend to downplay all the hard work that went into it; simplicity seems more persuasive than complexity. But the complexity is actually quite reassuring. Students and young researchers are often heartened to learn that physics is hard work and that it is okay for their own efforts not to look like a textbook presentation.[4] Messiness is the standard. Mistakes are normal. The great advances in sciences are much more remarkable when coupled with an appreciation that they came out of struggles and screwups instead of flashes of insight. The results of physics are not self-evident.

Every time physicists disagree on how to interpret a set of data, they provide fresh proof that physics isn't obvious. Some data only have significance from a certain point of view. Arno Penzias and Robert Wilson saw excess low-frequency noise in their antenna (shown in figure 2), not the cosmic microwave background. It was only when they looked at the noise in light of Big Bang cosmology that it seemed important.

The history of physics suggests that there are usually several ways to approach a problem. Quantum electrodynamics emerged from its predecessors not because it was clearly superior but because Freeman Dyson showed that the renormalization approaches of Richard Feynman, Julian Schwinger, and Sin-itiro Tomonaga were all equivalent. None of those independent approaches were wrong, they just needed to be reframed. Even the now-indispensable Feynman diagrams were not obviously useful when they first appeared. They were confusing, and it was not clear how to use them. Dyson, again, was instrumental to the acceptance of a new idea: He had to teach everyone what Feynman diagrams were good for and to evangelize about their importance. Things that now seem essential and obvious never started out that way.[5]

Physics needs many kinds of people

Turning complexity into good physics requires creativity. You can never tell what weird idea will help clarify a confusing observation or provide the key to interpreting an equation. History uncovers the strange stew of concepts that were necessary for the development of physics. Consider the second law of thermodynamics. Its formulation and interpretation were largely due to Lord Kelvin (figure 3). But Kelvin did not come to thermodynamics as a blank slate. He came to it as a Victorian obsessed with waste and engineering efficiency. He came to it as a religious figure who studied the heat death of the universe because it made sense in light of Psalm 102, which acknowledges that the heavens and Earth will all wear out like a garment.[6] His personal background gave him the tools he needed to grapple with the puzzling phenomena now attributed to the second law. You can see the importance of Kelvin's particular point of view when you compare his work with that of, say, German physicists working on thermodynamics. They brought very different ideas to the table and came up with different conceptions. The interplay of various approaches is what brought us

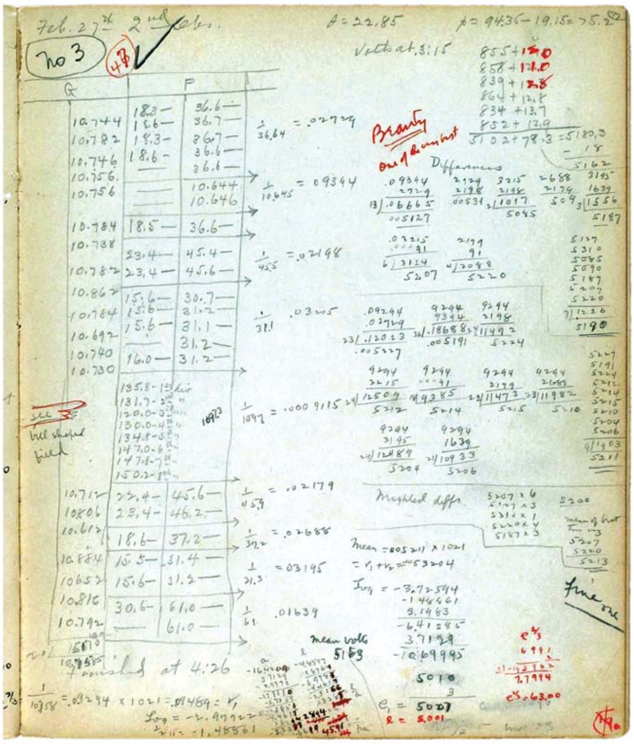

FIGURE 1. ROBERT MILLIKAN'S LAB NOTEBOOKS are filled with pages like this, jam-packed with data, calculations, corrections, and occasional comments. Despite the impression textbook presentations may give, perfecting the famous oil-drop experiment and obtaining the charge of the electron was a long, arduous task. This notebook entry is from 27 February 1912. (Courtesy of the Archives, California Institute of Technology.)

our modern view, which we wouldn't have if not for Kelvin's now-strange ideas.

Strange but ultimately useful perspectives often come from fields and disciplines apparently distant from the problem at hand. James Clerk Maxwell learned about statistical variation from historians. Particle physicist Luis Alvarez brought expertise in isotopes to his son Walter's geological work and helped solve the mystery of the dinosaurs' extinction. The history of science shows how important it is for scientists across different fields to talk to each other. Conversation among separate groups is healthy. Apparently isolated problems are often closely tied together, and you never know where you will find the weird idea that solves your difficulties.

The best strategy for encouraging diverse ideas is to cultivate a diverse community. Underrepresented groups that offer different ways of thinking are often the sources of fresh insights and novel methods. Numerous striking examples exist, and they have led to representatives of marginalized communities becoming visible in the mainstream. For instance, how Marietta Blau developed the nuclear emulsion technique—critical to the emergence of the field we now call particle physics—was distinctive of someone on the periphery. As a Jewish woman in interwar Austria, Blau, shown in figure 4, was doubly excluded. Women were often refused entrance to laboratories, sometimes on the grounds that their hair was too flammable. Jews were rarely allowed to hold high-ranking positions even before the rise of the Nazis. Such restrictions meant that if Blau wanted to study particles, she had to develop cheap, portable detectors that could be made with commonly available materials. With her techniques from the margins, she created an essential observational tool that was utterly surprising to those in the largely homogenous physics community of the time.[7]

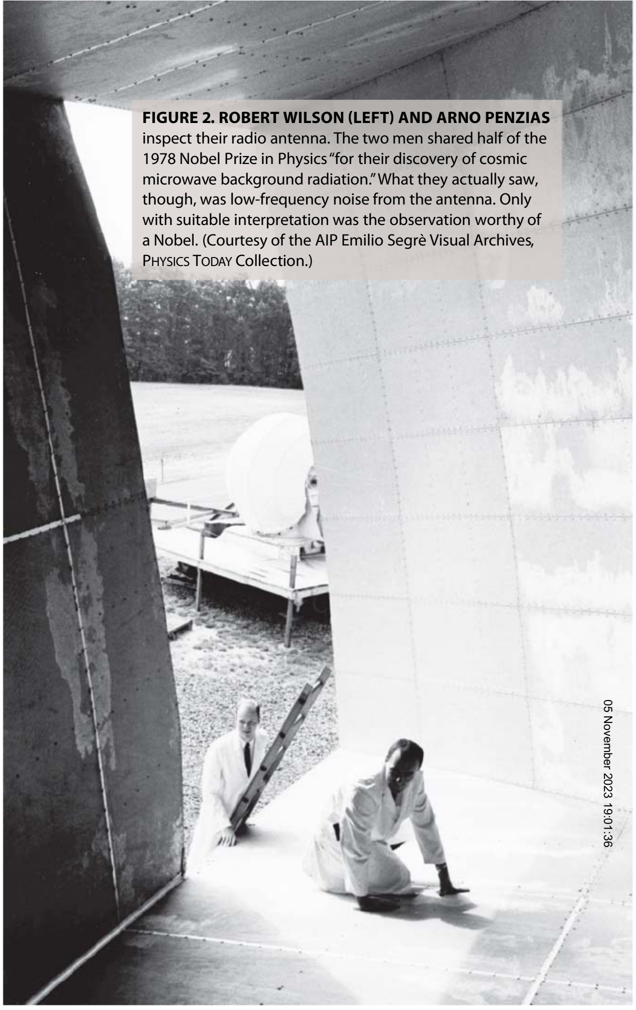

FIGURE 2. ROBERT WILSON (LEFT) AND ARNO PENZIAS inspect their radio antenna. The two men shared half of the 1978 Nobel Prize in Physics "for their discovery of cosmic microwave background radiation." What they actually saw, though, was low-frequency noise from the antenna. Only with suitable interpretation was the observation worthy of a Nobel. (Courtesy of the AIP Emilio Segrè Visual Archives, Physics Today Collection.)

Underrepresented groups are usually marginalized because of cultural inertia or deliberate decisions made long ago. For that reason, many working to increase diversity in physics see themselves as helping to right a social wrong. Feynman was denied admission to Columbia University because someone there decided it had too many Jewish students—a decision that now seems absurdly wrongheaded. Surely his alma mater, MIT, benefited from its decision to accept someone on the margins.

In 2015 John Roberts, chief justice of the US Supreme Court, was puzzled by the idea that diversity could be helpful in physics. (See Physics Today, March 2016, page 10.) Roberts's remarks were disappointing even if the idea behind them is not uncommon: The ideal of science as a monolithic enterprise of pure rationality effectively hides the importance of different perspectives and outlooks. However, that importance is clearly documented in the history of science, which can help clarify both why physics is mostly done by white men and why that can often be a limiting factor for future progress. The history of physics is a fantastic example of the importance of intellectual and institutional diversity. Many different ways of thinking can be brought to bear on a problem, and they should be encouraged.

Physics isn't finished

The diversity of ideas and interpretation serves as a reminder that physics is a work in progress. Knowledge is provisional. There are always new ways to tackle a problem, and there is always more to be learned. The history of physics should make one hesitant to claim that current theories will hold forever.

Some worry that such admissions of uncertainty make science less attractive. Actually, the opposite is true. If physics is nearly done, why pursue it? Placing the last few bricks in an almost-complete wall is not always exciting, but expanding an unconstrained structure is a thrilling challenge.[8] It is heartening to know that not everything has been discovered.

Accepting uncertainty would require changes in how physics and, more generally, science is taught. Physics is typically

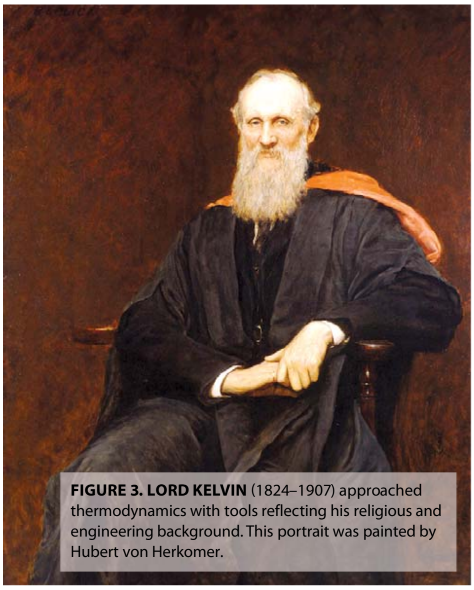

FIGURE 3. LORD KELVIN (1824–1907) approached thermodynamics with tools reflecting his religious and engineering background. This portrait was painted by Hubert von Herkomer.

presented as a list of things that physicists think are true. We call those lists "textbooks." They do a terrible job of showing what physicists and other scientists actually do—try to solve puzzles. Instead of talking about the things physicists already know, textbooks could emphasize what is still unknown about a subject. They could talk about how much work still remains: What are the mysteries yet to be uncovered? What is the problem that can't seem to be cracked? Curiosity should be rewarded, and everyone should be encouraged to ask, "What else?"

One effect of such a pedagogical shift would be less of a focus on proof. Few things can be strictly proven true. In practice, scientists accumulate evidence for a particular claim. That evidence provides some level of confidence. Insisting that every scientific concept meets or even should meet the standard of proof is dangerous; it makes knowledge easily attacked, since virtually every claim has some possible doubt.

If scientists are not explicit and honest about their doubts, a crisis of confidence arises when that uncertainty is revealed. That psychological reality is used to great advantage by, for example, those opposed to teaching evolution in schools. Talking about varying levels of evidence and doubt, instead of about proof or its absence, will actually make science more powerful in the public sphere.

Physics wasn't always as it is

The flip side of accepting that physics will be different in the future is accepting that it was different in the past. Everyone has a tendency to assume that the way things are now is the norm. But history makes it clear that things were not always this way. An understanding of why people used to think differently is a powerful tool for understanding people today. By drawing attention to older, unspoken assumptions, history shows us how to start paying attention to our own.

No less a personage than Einstein advocated for that historical method. As a young man, he read Ernst Mach's writings on the history of science, and he credited Mach with teaching him how to think critically about scientific principles: "A knowledge of the historic and philosophical background," Einstein once wrote, "gives that kind of independence from prejudices of his generation from which most scientists are suffering." (See the article by Don Howard, PHYSICS TODAY, December 2005, page 34.) He complained that physicists tended to regard currently accepted ideas as unalterable givens. Instead, he suggested, they should study the history of those ideas and understand the circumstances in which they were justified and found useful. In that way, a young physicist on the margins—say, one serving as a patent clerk in 1905—will feel emboldened to strike out into new areas and offer creative new suggestions.

History trains you to think critically about received ideas. History provides evidence of roads not taken. There are many ways to think about the mysteries of quantum physics. The ubiquity of the Copenhagen interpretation does not make it the best one, and it is certainly not the only useful one. Einstein himself would want physicists to take a critical approach to the foundations of quantum mechanics.

Historian and philosopher Hasok Chang argues that science's plurality of interpretations can make the history of science a resource for modern scientific research. He calls his approach complementary science—recovering forgotten and unsolved puzzles from the past. Some earlier ideas and observations, such as the reflection of cold, were simply abandoned rather than being investigated thoroughly and dropped for good reasons.[9] Putting complementary science into practice demands difficult self-examination. Thinking deeply and critically about assumptions and accepted knowledge can be hard to do in professional scientific contexts, but history is a mode in which it is encouraged.

David Kaiser's *How the Hippies Saved Physics* is a fascinating example of how that kind of critical thinking can happen.[10] Some physicists in the 1960s and 1970s were dissatisfied with the "shut up and calculate" culture of the field (four of them are shown in figure 5). They were interested in the deeper philosophical meaning behind their equations. To find that meaning, they engaged with both the mystical counterculture of the era and the history of quantum physics. Along the way, they helped to instigate broader interest in Bell's theorem and quantum entanglement. The simple realization that people used to think differently can be quite powerful.

Physics doesn't have rigid rules

People encountering the history of science for the first time are often shocked that the actual practice of science bears so little resemblance to the step-by-step scientific method they learned in school. Scientists simply do not follow a rigid, linear problem-solving system. Sometimes they start with a hypothesis, sometimes with a strange observation, sometimes with a weird anomaly in an otherwise straightforward experiment. Einstein himself reflected late in life that a scientist must be an "unscrupulous opportunist," adopting and adapting various approaches as new challenges arise.[11]

FIGURE 4. MARIETTA BLAU (1894–1970), as a Jewish woman in interwar Austria, was excluded from the center of physics action. From the margins, she created the nuclear emulsion technique. (Photograph, from 1937, courtesy of the AIP Emilio Segrè Visual Archives, gift of Eva Connors.)

Instead of applying a rigid method, scientists work with whatever evidence they have and make the best explanation possible. Consider the claim that theories are disproved by contrary observations. In the early 19th century, Uranus's orbit seemed incompatible with Newtonian gravity. One reaction would have been to declare that Newtonian gravity had been disproved. Of course, very few people did that. The Newtonian theory of gravity had proven so fruitful that much more than one anomalous observation would be needed to discard it. An easier resolution to the problem was that a new planet, Neptune, was hidden in the darkness. So it seemed obvious that a later discrepancy in Mercury's orbit should be explained the same way. To again redeem Newtonian gravity, astronomers searched for a planet Vulcan hidden in the Sun's light. Eventually, however, Einstein proposed that Mercury's orbital anomaly was a good reason to scrap Newton in favor of his own theory.[12]

Sometimes a discrepancy is a good reason to discard a theory, and sometimes it is worth inventing a whole new entity to save a theory. Different situations call for different approaches. Physicists usually have good reasons for making their choices, but they need to acknowledge the difficulty and complexity of those choices.

The stories told about scientific discoveries matter. One can easily find completely different versions of the origin of special relativity. Was it a straightforward deduction from the results of the Michelson–Morley experiment? Or did it come from Einstein's philosophical ponderings of the nature of space and time? Or, historical origins notwithstanding, should it just be derived abstractly from Maxwell's equations? You conceptualize physics in different ways depending on which story you hear. Those who do the telling should make sure their stories are the ones best supported by the historical evidence.

One should not get too anxious about work that seems to endanger the scientific method. There are many ways to go about doing physics, and it was probably not fair to attack string theory for violating methodological guidelines, though string theorists might want to heed the earlier warnings about being overly attached to beautiful theories. Physicists nowadays are typically not trained in the philosophy of science—although both Einstein and Niels Bohr were—and the philosophical principles they invoke are usually far out of date. Karl Popper's notion that the mark of science is falsifiability doesn't do much work anymore—for example, astrology is perfectly falsifiable, but it's not considered science. Even the currently popular Bayesianism can only take one so far. The history of science shows how definitions and standards of science have shifted over time and, hopefully, provides some impetus to engage with the important work being done today by philosophers of science.

Ideas on their own terms

History teaches that knowledge is not fixed. Historical thinking involves asking incisive questions: Why did people in the past think that was true? Why do I think the opposite is true?

Engaging with history will teach you to understand ideas on their own terms. Aristotle wasn't a man who was bad at Newtonian physics, he just had a completely different perspective. People in the past worried about different things and tried to solve their problems in different ways. The bugbear of historians is the so-called Whig history that judges everything in the past by how much it looks like the present. Eschewing that kind of judgment is an amazing tool for making sense of the world and its people. If you can understand why people believed heat was a form of matter, you can understand why your colleague is being intractable in a meeting.

Historical thinking makes its subject dynamic. It helps you think about science as a series of questions rather than a series of statements. Those questions

FIGURE 5. THE FUNDAMENTAL FYSIKS GROUP, founded in Berkeley, California, in 1975, explored both mysticism and foundational quantum physics. Shown here are four members: Standing, left to right, are Jack Sarfatti, Saul-Paul Sirag, and Nick Herbert; seated is Fred Alan Wolf. (Photograph by Fred Alan Wolf.)

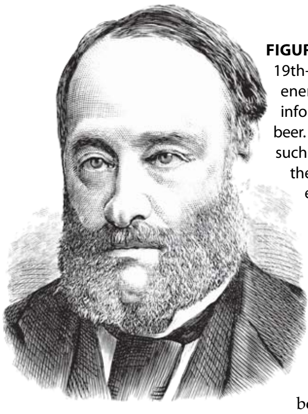

FIGURE 6. JAMES JOULE'S 19th-century exploration of energy conservation was informed by his expertise in beer. History of science reveals such tidbits, which makes the study of physics more enjoyable. This etching of Joule first appeared in the May 1874 issue of the *Popular Science Monthly*.

will continue into the future, and it is helpful to know what has been asked so far.

I would be remiss not to mention that history of science is, frankly, fun. It is full of fascinating stories that will captivate you. Who doesn't want to know more after learning that in his experiments James Joule (figure 6) relied on his expertise in beer, or that Newton stuck a dagger into his eye to learn more about colors?

I've heard concerns, though, that such stories are a distraction that take time away from science instruction or quantitative research. A good strategy is to integrate history into teaching and thinking. Doing so will make physics majors and physicists better citizens of the world and help attract sharp students to science careers. Even for nonscience majors, history of science is an excellent way to increase science literacy and engagement with scientific ideas.

In the end, history of science exposes scientists to new ways of thinking and forces them to reexamine what is already known. Such intellectual flexibility is essential for any discipline, but it is particularly important for fields as influential and authoritative as physics and other sciences. How do we know what we know, and how might it be otherwise?

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