Chapter 14
Science Education in the Post-Truth Era

N. G. HOLMES
Laboratory of Atomic and Solid State Physics, Cornell University,
142 Sciences Drive, Ithaca, NY 14853 USA

Anna MCLEAN PHILLIPS
Laboratory of Atomic and Solid State Physics, Cornell University,
142 Sciences Drive, Ithaca, NY 14853 USA
and
Tufts University, Department of Physics and Astronomy,
574 Boston Avenue, Medford, MA 02155 USA

David HAMMER
Tufts University, Department of Education, 12 Upper Campus Road,
Department of Physics and Astronomy, 574 Boston Avenue, Medford, MA 02155 USA

Abstract. We argue there is an urgent need for science education to respond to the societal phenomenon of "post-truth," to do much more in supporting students to understand how science constructs and reconstructs “truth.” This is not to abandon canonical content but to prioritize essential objectives. Students should develop a sense of how science arrives at and refines ideas; the messy complexity of the process; what sort of questions it can address; how it evolves and interacts with culture and community; how it can result in reliable knowledge and how it can go wrong. We draw examples from introductory physics laboratories.

1. Introduction

The editors invited us to reflect on what physics education research might have to say about “the post-truth era.” We are happy for the opportunity, because we do see a connection to physics education, although the phenomena of concern go beyond physics.

1.1. The Idea of Post-Truth

At the start of 2017, the new press-secretary Sean Spicer claimed, “This was the largest audience to ever witness an inauguration, period.” He said that despite plain, compelling photographic evidence that the attendance was much smaller than at President Obama’s inauguration in 2009. This is what people mean by “post- truth”: an apparent disregard of evidence.

If there is a post-truth era, though, it started long before 2017. Stephen Colbert was talking about “truthiness” in 2005, in reference to disregard of evidence concerning the Iraq war. In that case, the public did not have direct access to evidence; we had to consider secondary reports of it and, if it mattered to us, make judgments about their reliability. As we the authors write this chapter, the matter of President Biden’s election is still in the news, with ongoing challenges to its validity.

“Post-truth” was the Oxford Dictionary’s Word of the Year for 2016, defined as “relating to or denoting circumstances in which objective facts are less influential in shaping public opinion than appeals to emotion and personal belief” [1]. We cannot rely on that definition, however, for our purposes here, because it begs a question that is pivotal to any reflection on science and science education: What are "objective facts"?

To his credit, in a way, the press secretary felt the need to rebut the counter-evidence to his claim, arguing that the use of "floor coverings" on the mall made the photographs misleading. President Trump's counselor, Kellyanne Conway, famously defended her colleague by saying he "gave alternative facts." But what motivated those facts? The claim was similar to previous claims about Iraq (that it was responsible for the attack on the World Trade Center, that it had weapons of mass destruction), and it is similar now to claims about the election: There are efforts to refute evidence for widely accepted conclusions, but there is no evidence to support the "alternative facts." Still, many people seem to believe them.

Perhaps the name "post-truth" is misleading. Is it plausible that people do not care about what is true? There must be conviction driving people who, for example, put themselves at significant risk storming the Capitol Building. Maybe the problem isn't so much *caring* about the truth as it is in deciding what truth is. Rather than ask "why don't people care about truth," we might ask, "How do people arrive at their truths?" What are the means they have available, from their communities and from their schooling, for forming, considering, assessing, and refining their beliefs about the world? Clearly people have many ways [2]: from tradition (it's what our people have always thought); from affiliation (it's what my people think); from commitments of values, authority, deduction, or what just seems obvious.

1.2. The Denial of Science

Scientists and science educators have written about the problem in terms of politicians' and the public's "denial of scientific evidence" and "rejection or ignorance of scientific expertise," as Kienhues *et al* put it, "the heart of *post-truthism*" [3, p. 144]. There have been many examples over the years, such as with respect to climate change or, most strikingly this past year, COVID-19. Again, and like Kienhues and her colleagues, we argue there is more to consider. Again the term *science denial* may be a misnomer: The public and the honest science-denying politicians (some may not be honest!) may not understand what science is or how it constructs truth. Most of what they experienced of science in schools asked and graded them for accepting the authority of their teachers and texts [4, 5]. Perhaps it is not science they are denying, *per se*, but "science" as they know it, the practices they learned in school of senseless memorization and submission to authority.

The case of COVID-19 is most striking, and fresh in our minds, so we'll focus on it. Again, the claims in the news have offered the public only secondary reports of evidence–about the disease, its origins, what measures are needed to stop it spreading, how it might be treated. People have had to make judgments about what to believe. Often that has entailed navigating conflicts between what they hear science says and the beliefs they have constructed by other means, what their communities think and trusted leaders say, and/or what makes sense to them by their intuition and experience.

Most challenging, the "facts" have kept changing. In February 2020, the public was told not to buy masks, that masks were essential for health care workers but not important for the general public. A month or two later the advice was different: Science said the evidence was very much in favor of masks for the public. For most of the year, there was strong emphasis on washing hands and sterilizing surfaces, even suggestions to sequester mail and groceries, based on studies of how long the virus survived on surfaces. More recent evidence suggests the risk of transmission by contact with surfaces is low. And so on: Science keeps changing its mind.

For those familiar with science and how it constructs knowledge, all of that is to be expected: What seems to be true shifts over time, with evidence, with theoretical progress and new calculations. The construction of truth in science takes time and is always to some degree uncertain. Depending on the question, the data available, and the approaches to research, that uncertainty can be larger or smaller—very often, the "conclusions" at any moment can only be tentative. In the early months of COVID-19, epidemiological data (what happened on the Diamond Princess cruise ship, for example) were, by their nature, difficult to analyze. They were the data that were available, and scientists did the best they could. Students of science learn about "the test of time," a shorthand for years of theoretical and experimental argumentation, but in a public health emergency it becomes important to act before the data undergo "the test of time."

Naturally, too, scientists remain human, and humans are "fraught with all kinds of imperfection and deficiency," as Ibn al-Haytham put it 1000 years ago [6]. The construction of knowledge is not infallible—science, after all, promoted the idea that there are different races of people [see 7, for example], with different levels of ability, and scientists held that idea for many years before rejecting it. The idea failed the test of time, but it has obviously had lasting, terrible consequences for humanity. It is for this reason we do not advocate for education to support blanket deference to science, but for education that will enable people to make better judgments about when and how to consider what science has to say [3, 8].

Today there are vaccines and the news reports that they are effective and safe. For those familiar with randomized controlled trials and statistical power, these findings are far more reliable than the results from epidemiology—to be clear, this is not at all to disparage epidemiology; it is to recognize that testing the safety of a vaccine is amenable to controlled study, which greatly helps to reduce uncertainties. (Of course, those familiar with the particular subject matter have still more basis for accepting the findings.) For others, the reports of vaccines' effectiveness and safety could easily seem like the latest best guesses, maybe to change like other advice over the year.

None of that is about physics *per se*, but in what follows, we argue that physics education can and should contribute to helping students experience and better understand how science seeks and assesses truth—*some kinds of truth*, that is, such as about the climate or COVID-19. The ways that truth-seeking happens are messy and changing; new ideas in science often imply new methodologies. That makes it difficult to define; Einstein thought determinism was necessary for science. For our purposes here, we take science to be a pursuit of knowledge about the natural world that is typically based on uncertain evidence and on reasoning that includes assumptions, approximations, and simplifications. Something comes to be true in science because the community finds it to fit with other ideas and with observations.

Perhaps most important, anyone can be wrong, including scientists; that, in fact is much of what science has to offer, epistemic practices that expect even obvious ideas can be wrong. We will argue that the best response for science education to the post-truth era–and an urgent need–is to place much more emphasis on learners' experiencing the messiness and contingencies involved in doing science themselves. They should experience how apparently obvious "facts" can turn out to be false, as well as how doing science can sometimes lead to reliable conclusions, "facts" worth accepting as true. Thus, we hope physics education can help address the phenomena of "post-truth" both as they concern science directly, such as in COVID-19 and climate change, and as they concern more general matters of evidence and argumentation, such as election results.

1.3. The Structure of this Chapter

We begin with a brief discussion of "How truth is constructed in physics," highlighting the messiness and ambiguities and uncertainties that physics curricula, in their focus on the canonical content, tend to set aside. We reflect on the role of community, including judicious reference to others' expertise as well as the importance of the community's hearing and considering multiple perspectives, and on how the history of physics is filled with examples of radical, initially unthinkable ideas eventually folding into the canon. The next section, "Doing physics in physics class," describes and presents some examples of classroom activities shifted to focus on the goal of students learning how truth is sought through inquiry.

In the closing sections of the article, we step back out again to consider the urgent needs for physics education to transform, in response to the phenomena described as "post-truth" and "science denial." We reflect on how physics education sits within and can manifest larger societal dynamics, often to the effect of limiting who participates and how. Finally, we reflect on some of the challenges for teachers and propose elements of a reformed agenda for teacher preparation.

2. How is Truth Sought and Assesed in Physics?

The history of physics is filled with accounts of how ideas that once seemed true—that objects return to rest if they are not caused to move, that space and time are independent, that the cause-and-effect laws of physics are local and deterministic—turned out to be false or limited in validity. There are, of course, debates among philosophers over the nature of scientific progress. Kuhn wrote of "scientific revolutions" [9], arguing that the shifts of views are so dramatic as to make them "incommensurable," challenging Popper's account of "falsifiability" [10]. But it is clear that *being wrong*, and being confused or uncertain, are staples of experience in physics.

2.1. Checking How Ideas Might Be Wrong

Practices of research in physics revolve around considerations and procedures for checks of how an idea or fact or measurement might be wrong or uncertain. Moreover, these checks are part of the motivation and joy physicists experience to discover a gap or inconsistency. As we write this chapter, there are many physicists gleeful over a discrepancy from theory in a recent measurement of the magnetic moment of a muon, which might mean the current theory, the "standard model," needs revision. These checks are part of the pleasure for individuals, as well, to discover a confusion they can work to resolve and for the experience of the pleasure in that challenge [11].

The moral for physicists is that what seems to be true is always, in principle, to some degree uncertain. Nothing is ever *absolutely* certain, but over time the uncertainty can become so small the community starts to ignore it. Ideas and findings come to be accepted as true if they pass the test of having survived challenges of counter-arguments and counter-evidence. By some accounts, the time to be most sure of a theory is when the community has established when it fails—that is when one can see the boundaries of its domain of validity [12].

The moral is explicitly recognized in the community and culture of physics: things that seem true can be false, so do what you can to check for that possibility. It may not be so explicitly recognized that the practices of checking keep evolving themselves or deciding what assumptions and previous ideas need revision is a complex, messy process. One might think, and physicists often say, that the bottom line is what experiments show, that physics is an empirical science, but evidence from the history of science challenges that simple story.

Consider two examples. The first is from the late 1920s, in measurements of β decay. In this process, a neutron decays into a proton and an electron, which fly apart at high speed. The problem was that the sum of the energies of those two particles fell short of the theoretical prediction; the process also seemed to violate conservation of momentum and of angular momentum. In 1930 Enrico Fermi posed the idea of a neutrino as a tiny, neutral, and, as far as he knew, *undetectable* particle that is emitted during the interaction. This idea was initially rejected; science needs experimental verification. But over time, it came to be taken seriously based on its theoretical, explanatory power: Allowing an undetectable "ghost" particle was preferable to allowing an exception to well-established conservation laws. Eventually, physicists found ways to detect neutrinos and they are now firmly established in the canon. Fermi's initial idea was correct but included one key mistake: just because the neutrino was undetectable by experiments at the time did not mean it was *fundamentally* undetectable [13].

The second example is of another theoretical proposal. In the late 60's, astronomer Vera Rubin found that the rotational speed of galaxies could not be explained by the measurements of mass distribution and well-established models of gravitation. If most of the mass in galaxies were concentrated in the stars of the galaxy, as was assumed through most of the 20th century, one would expect the stars near the edge of the galaxy to orbit more slowly than ones near the middle. Rubin observed that the rotational velocity of stars near the edge remains approximately constant. Perhaps, she suggested, there is dark matter, unseen mass distributed throughout galaxies, as had been proposed as early as the 1930's. Some of the initial reaction was to question the quality of her observations (questioning that was no doubt tinged with sexism [14]). However, Rubin's findings and the idea of dark matter became mainstream faster than Fermi's did for neutrinos; the community seems to have been more willing to prioritize theoretical coherence without empirical evidence. To this day, nobody has directly detected dark matter, yet one would be hard pressed to find a physicist that doubts it exists. (Whether or not physicists will one day be able to detect it, however, is a lively debate.)

Of course, there are many other ways that the epistemological values of physics—the values for what gets to count as evidence—have evolved. Over the 20th century, quantum mechanics brought dramatic change in physicists' expectations of a valid, complete theoretical account of phenomena. Einstein was famously unhappy about it, claiming that "God does not play dice," developing careful arguments that quantum mechanics must be incomplete [15], even writing in private correspondence that "if all this is true then it means the end of physics." [16].

Some of that evolution has differentiated subfields. High energy physics, for example, relies on the "5 σ" criteria for a measurement to count as a "discovery." The measurement must be in the very tail of the predicted normal distribution, equivalent to a p-value of 3 x 10^{-7}, far beyond what is used in most other scientific fields (such as the social sciences with the $p < .05$ threshold). This threshold is made possible and necessary by the fact that they are working with a *tremendous* amount of noisy data: The particle collisions in the LHC generate an astonishing peta-byte of data per second [17]. Condensed matter physics, in contrast, needs to pay more attention to systematic effects than to statistical noise and so there is not a corresponding sigma-level threshold for accepting a measurement. The condensed matter physicists still have to contend with and seek to minimize those systematics, but, overall, their criteria for measurements are much more about apparent trends in the data. Von Klitzing's analysis of the integer quantum hall effect, for example, though containing extensive accounting of uncertainties and systematics, the voltage "clearly levels off" when the conductivity and resistivity "are zero" [18].

To summarize so far, we have highlighted how the approaches in physics for con- structing, assessing, and revising what the community takes as true can be messy, vary and evolve, and are connected deeply by theoretical and experimental understandings. Throughout, though, what remains stable about doing physics is that it involves deliberately looking for reasons to disbelieve an idea or identify possible inconsistencies and gaps. Many ideas do not survive; that is part of doing physics: the positing and rejection of ideas. As well, the practices and values support questioning any idea, including long-held views, as new possibilities for challenging them arise.

2.2. The Limited Roles of Authority and Tradition

In these ways, the practices of constructing and assessing what is true in physics, and in other sciences, places much less value on authority or tradition than other means of seeking and assessing truth in society. That ideas have been in place for centuries or millennia, or that they are advocated by established figures, are reasons to give them consideration, but they are not—at least not explicitly—sufficient reasons for their acceptance in science. This is in contrast with other approaches to deciding what is true in society and it is in contrast with how science is often depicted, perceived, and taught. Part of our motivation for writing this chapter is that traditional pedagogy—the physics community *is* driven by tradition in pedagogy—tacitly encourages students to accept truth by authority, very much in contrast to the practices of physics [19]. We have more to say about pedagogy below.

The perception of physics as authority-driven is certainly not what physicists aspire to and it is in conflict with disciplinary values of pushing boundaries and seeking inconsistencies in theory. Although Fermi's theory of neutrinos did not fit with the understandings of particles at the time, the community was eventually compelled by the evidence to shift from the previously established "truths." The practices and values of physics support questioning any *person*; the cultural aesthetics of physics and science do not respect deference to authority. It would sound odd to say "Fermi said" or "Rubin said" as the way to support the existence of neutrinos or dark matter.

One might, however, say "Fermi found" or "Rubin showed," respecting the scientists' expertise but pointing toward their having gone through some process of derivation or empirical study. And their standing in the field would become part of that support. To rely on others' expertise is certainly within the values and practices of physics; not as blind trust or obedience, but out of a general understanding of the nature of that expertise and how it works. In evaluating a scientific claim, result, or methodology, a physicist (or scientist generally) makes a decision about when to think deeply through the ideas themselves and when to respect and rely on the expertise of others. If the approach seems inconsistent with epistemological values, one might choose to take more care, perhaps studying the arguments more closely, perhaps checking with others in the field.

That's within the explicit values of the discipline. There is a similar explicit respect for tradition; one does not reject a long-held idea the moment there is counter-evidence, physicists will certainly work to find explanations that remain consistent with previously established "truths." Consider, for example, the response to physicists who claimed to have measured neutrino velocities faster than the speed of light. Their findings were met with intense skepticism and close examination of their work revealed small but essential flaws.

2.3. The Persistence of Biases

We have been describing the values of the discipline, more precisely the *epistemic* values, but it is essential to acknowledge that they are not all that drive how truth is constructed. There is abundant evidence that physics has not been successful in managing social biases, which affect who participates and rises to prominence in the field. By the explicit epistemic values, the fact that Vera Rubin was a woman should not have had an effect on the perceived value of her work—but it did.

There are numerous examples of how implicit (or explicit) biases have led to voices being excluded from physics; from the female "calculators" (particularly women of color) at NASA being disregarded for their contributions to the space race to Marie Curie and others being denied faculty positions. Many would argue the issues of sexism and racism in physics are much more subtle today than in the past. However, biases in everything from citations [e.g., 20], grant funding [e.g., 21], hiring decisions [e.g., 22], reference letters [e.g., 23], teaching evaluations [e.g., 24–28], or grades [e.g., 29–36] impact whose voices, and thus whose results and claims and evidence, are heard, celebrated, and re-voiced. This further leads to a negative feedback cycle where women and people of color do not see themselves in the authority figures being celebrated and are further alienated from the field [37, 38]. These issues directly impact the progress of physics and what and whose truths emerge on to the field.

Ultimately, physicists are humans and what really happens in the community of physics does not always match its aspirations. There are social dynamics as in the rest of society. An individual's sense of truth is not simply an individual sense. Truth is motivated by the beliefs and values of the individual's community (or communities). To fit into the community, to be respected and valued by them, one must generally take to be true what they take to be true. The trust in the community also translates into trust in the community's beliefs. Our trust in science led us to get vaccinated and wear masks, but we were all surrounded by colleagues, friends, and family who were also vaccinated mask-wearers; we were influenced by surrounding cultural values. The same goes for the cultural values of physics and the physic classroom. While aspects of these social dynamics may be problematic, the humanity of physics is an important part of its identity and culture. Only by making it more explicit (throughout physics and physics education) can we strive for change.

Our core claim in this chapter is that the messy, complex, and evolving set of practices and values in how physicists seek, assess, and revise "truth" should reflect in what students experience. Not only are these practices and values essential features of the discipline, as we and many others have long argued [39–41], they are also of urgent priority for society's grappling with post-truth. In the next section, we discuss and give examples of how physics class might change to support students' learning about how science pursues truth.

There are challenges of course, in providing students such experiences and in coordinating with goals of their learning the canon (which we do not propose to abandon). One challenge, clearly, is that the time scales of historical progress in professional physics are years and decades, not the days and months that are available in school. Other challenges include views about schools and assessment long accepted as "truth" that we argue need to change.

3. "Doing Physics" in Physics Class

It is, we and others argue, an urgent objective for science education to prepare students to be sophisticated consumers and critics of claims and arguments they hear in the world, scientific or otherwise [42]. Our purpose here is to consider how physics classes might contribute to that objective by giving students their own experiences of doing physics and engaging in their own pursuits of knowledge about phenomena.

To summarize the previous section, *physicists are professional learners*, so learning physics should mean learning how to learn. That includes developing the discipline to revise what you believe based on evidence and reasoning; learning to expect that you'll be wrong. Learning in physics (by physicists and by physics students) forces humility, as ideas that seem like they have to be true often end up needing revision.

This has to be at least part of why physics has a reputation for being more difficult than humanities and social sciences (which also work on "truth"): it happens so much more often that you find out you're wrong. The practices of the discipline, and the nature of the knowledge it produces, allow learners to see contradictions in theoretical calculations or unexpected results from empirical investigation. If you expect the period of a pendulum does not vary with amplitude, for an example we'll discuss, and you take careful measurements, you'll have to contend with data that doesn't agree.

In the social sciences, by contrast, it's not so easy, or perhaps we should say *forced*, to find out you must be wrong about something. To be sure, that is a challenge for us right now in this chapter: Many readers have the strong intuitive sense that students must come away from physics class with *correct* understanding and we are arguing for a different urgency, that students come away with a rich sense of how "correctness" comes to be. While we do not propose abandoning canonical objectives, we are contesting their priority. But we do not have "objective" means of forcing the point. In matters of educational objectives and assessment, it is harder to know when you're wrong. (That has to be part of why progress in education is more difficult than progress in STEM fields.)

The salience of being wrong is precisely why, we argue, physics class provides a wonderful opportunity for cultivating epistemic virtues, including humility, open-mindedness, and attention to multiple lines of reasoning. To take advantage of that opportunity, however, means shifting from that overriding focus on *correctness*, which so often has students accepting ideas by authority (if only for the purpose of a good grade) rather than as a result of having *done physics* for themselves.

It will help to have some examples of how that shift might happen. For this chapter we focus on what students experience in labs.

3.1. Two Examples of Labs

For many decades, physics teachers have assigned students to replicate Galileo's findings about pendula, in particular that the period is independent of the mass and amplitude. He was right about mass and wrong about amplitude, the age-old moral is that *even Galileo* could be wrong; science is about evidence and reasoning, not authority.

We have used this as our first lab in our introductory courses, guiding students to make their measurements precise. The tools have changed over the years, but one old, simple approach is to time swings by hand with a stopwatch, let the pendulum swing 5–10 times, and divide the total time by the number of swings. That's good enough for students to get their measurement uncertainties small enough to see the not-quite-as-small deviations from the result they had expected to confirm [see 43, for sample data].

Students using this method typically find evidence there is some small dependence on amplitude [43]. That's not what Galileo said and that's not what the equation says ($T = 2\pi\sqrt{\frac{L}{g}}$) for those who have seen it in their textbook or searched for it on the web. When faced with this contradiction, many students stall, re-estimate the size of the uncertainties in their measurements, or write it all off to the catch-all "human error." Some even manipulate their data to obtain the desired outcome [44].

Why? Their expectation (their framing of the situation [45, 46]) is that the lab should verify the known result; known by the authority of the instructor, the textbook, Galileo. Authority is often the principle way they have learned to arrive at truth in their schooling, especially in science courses [47, 48]. It's not irrational, that approach to arrival at truth. It certainly makes sense in school to trust the authority, particularly when that same authority (or its agent) will be scoring your tests and assigning your grades. And as we discussed above, it often makes sense in science: Should a single, two-hour experiment be enough to "disprove" apparently established findings in the field?

In the investigation, we are after students' learning to do science for themselves, to see their methods produce a discrepancy from Galileo's claim. It is appropriate for them to take the authority seriously, as physicists respect the authority of their colleagues in other disciplines, but they should take their own findings seriously as well. We are after their working to grapple with the discrepancy, to examine their methods, compare their findings to other groups', to wonder if there's something so many of them could be doing wrong. Part of learning physics is learning that findings like Galileo's should be replicable; anyone ought to be able to make a pendulum and see what happens.

Here is another example, used by the first author to follow the pendulum lab. Students by this point have studied two possible models for objects moving freely through air: a gravity-only model and a gravity+drag model [49, 50]. The lab activity begins with students predicting the acceleration of an object on the way up and on the way down according to the two models. The gravity-only model predicts the acceleration to be 9.8 m/s^2 in both directions, while the gravity+drag model predicts the acceleration to be less than 9.8 m/s^2 on the way up and greater than 9.8 m/s^2 on the way down. The lab is designed, again, for students to encounter a contradiction and this one is striking: When they measure the acceleration of a beach ball, they find it to be less than 9.8 m/s^2 in both directions.

In our observations of students in this lab, many grapple productively with this contradiction; that it follows the pendulum lab helps them frame the lab as something other than a game in confirmation. They check calculations, retake data, systematically consider the forces on the object, or begin to invent a mysterious constant upwards force on the ball [50]. Almost as many groups, however, engage less productively: For some, it seems, the pendulum lab was not sufficient to disrupt a confirmation framing; others apparently focus mainly on getting done with the lab as quickly as possible [49].

It is rare for a group to settle on an explanation for the discrepancy by the end of two-hour lab period, but that is not our goal. We see their struggles themselves as scientifically productive. They are opportunities for *problematizing* [11, 51, 52], a core part of doing physics, identifying and articulating inconsistencies in one's knowledge or understanding. Successful groups in this lab are those that arrive at identifying and articulating a problem: There seems to be some other force acting upward on the ball, but they do not know what it is. Some groups might come up with buoyancy as a conjecture, but that is not the instructional goal of the lab (although when the topic of buoyancy comes up later in lecture, later in the semester, data students have from the lab can certainly contribute).

3.2. A Focus on Students' Learning About Empirical Investigation

The instructional goals of these labs are that students learn how to learn about the physical world and to experience doing physics for themselves–that is, to experience some of the disciplinary practices of working toward "truth." It is something they can do, for themselves; it involves uncertainty, simplifications, iteration, and continual refinement. Many students have difficulty with this reframing, particularly as it is one with which they are not familiar, which we take as evidence of the need for labs like these.

To be clear, the instructional purpose is not simply to focus on scientific skills and practices [53]. Too often, a focus on skills (e.g. the control of variables strategy, hypothesis formation, algorithms for error analysis) can lead to a sense of science as comprised of a trivialized set of procedures [54–57] that one must implement to obtain objective truth [19]. The notion of developing a sense of the practice of science *must* include all the messiness and subjectivity and uncertainty that is inherent in the practice of science. Students must have the opportunity to enact their agency to critique claims and construct their own [48, 55, 56, 58]. That is to say, the epistemology of science must be explicitly attended to such that the process is not overly simplified to a set of routine procedures.

While this seems like a lofty goal, physics activities at the middle school [59], high school [60–62], and college levels [43, 58, 63–70] have found ways to do this successfully. In these examples, students are not necessarily exploring novel questions whose answers are unknown in the scientific community and therefore could lead to publishable results, although this is a direction many college-level biology lab courses have been taking through Course-Based Undergraduate Research Experiences or CUREs [71]. In fact, recent work has proposed that the pursuit of an authentic (i.e., novel, publishable) research question is not a requisite for the learning benefits from CUREs [72, 73] or even undergraduate research [74]. Instead, the important feature seems to be that students engage in an experiment where the outcome of the investigation is not predefined–where the students do not know (and better yet do not believe the instructor knows) what answer the experiment should produce [69].

This reframing presents a tension for the possibilities of developing core concepts and ideas alongside scientific practices and epistemology. This tension has been excellently articulated by others elsewhere [e.g., 19, 75], identifying the potential shortcomings of curricular reforms that maintain a focus on canonical knowledge alongside a focus on scientific practice.

For us, and the teaching assistants (TAs) we prepare for this different sort of work, it is essential to recognize that the pendulum experiment is not about teaching students about pendula and the free-flight experiment is not about teaching students about buoyancy. Rather, they are about cultivating students' understandings of empirical investigation, and that objective would be at odds with goals to verify or demonstrate particular phenomena. If the labs are to provide students experience of what it means to learn as nascent physicists, then there must be room in them for students to devise their own procedures, to grapple with uncertainties and ambiguity, even to find and explore their own conjectures and questions–we speak of welcoming and cultivating students' "epistemic agency" [76].

3.3. The Importance and Challenges of Engaging with Multiple Perspectives

It is a wonderful feature of physics, that everyone has experience of it. That includes widely shared experiences of motion and forces, of sound and light, of magnets. It also includes particular experiences not everyone shares, a variety among students of different sports, jobs, tools, musical instruments.

It's not enough to make room for these experiences: The instructors–ourselves, our TAs–need to respect and engage with what students do and think and to teach them to do the same with each other. This is, again, how doing physics works to seek, assess, and revise what to accept as true, by attending, interpreting, and responding to arguments and counterarguments, evidence and reasoning. A great deal of work has focused on the importance of argumentation in science [77]; labs are wonderful spaces for it to happen. Novel, unfamiliar perspectives are valuable.

This, of course, is part of the challenge of participating in these labs, for students as for instructors, to hear and make sense of someone else's thinking, especially if it is novel, especially if they express it in unfamiliar terms. As it has been for physicists, it can be challenging for instructors and students to manage implicit biases cued by others' race, gender, accent, or appearance — part of learning the discipline is learning to manage those biases. Cultivating practices of doing science means supporting students in these efforts.

Too often an individual's personal cultural values are pitted against the cultural values of the discipline, pushing students out of physics and thwarting any sense of trust in the culture and activities. There are tensions, no doubt, but the overlap in values is much larger than we typically give credit [78].

4. Final Remarks

We began this chapter suggesting that "post-truth" may not be precisely a matter of people not caring about truth; to the contrary, people seem confident, attached, and deeply caring about the truth as they see it. The problem, we posit, is in how they arrive at and maintain those commitments. And, we suggest, the essence of "science denial" is that people do not know what science is.

Findings from Physics Education Research have shown repeatedly that traditional pedagogy promotes counterproductive epistemologies [79–82] assess students' learning physics as information to memorize, provided by authority, that need not connect deeply with their experience of the physical world. To succeed in school, most learn to set their sense aside; the focus is more on students' obedience than it is on their developing the discipline of mind physics has the potential to teach. It should come as no surprise that later, when they are out of school and don't need to care about collecting points or being obedient, many come back to trusting their own sense of the world, sticking with their own means of deciding what is true. For those who stay obedient, accepting what science says as true, it must be jarring when science says one thing and then later changes its mind.

We have argued for a shift in priorities in physics education toward giving students experience in doing physics for themselves. We focused on what can happen in introductory laboratories, largely because we suspect labs are the easiest places to start. They are typically only loosely connected to the lecture portions of classes, and there is strong evidence that traditionally designed labs fail in the goal of reinforcing lecture content [83]. It is, however, also possible and important for the shift in priorities to reflect in lecture portions of courses. There has been a great deal of work there as well, toward reform of lectures and discussion sections [11, 84], although relatively little so far to prioritize students' epistemological progress [85].

Scoping out still further, the arguments we have presented here apply to other sciences as well. Most of what happens in introductory physics is amenable to controlled experimentation, but for the epidemiology of the pandemic, climate change and other matters of societal importance, scientific investigation takes place mainly through observations. Other introductory courses would be better positioned to give students experience problematizing, constructing, and refining knowledge with data collected from events in no one's control, such as in evolutionary biology or astronomy. While different scientific fields and subfields have their own "epistemological culture" [86] that determine what types of experimental and observational data are valued and are used in constructing knowledge, working with ambiguity and limited data are common activities across the sciences. So too is working towards a collective understanding through robust debate [87]. Exposure to the diverse ways in which scientific subfields construct knowledge and settle on truth by muddling through that ambiguity in multiple educational contexts will serve to further students' ability to scientific information in their everyday lives.

We have suggested that a shift in priorities, such as we have illustrated can happen in labs, could contribute to addressing the problems of science denial and post-truth. Experience doing science might help students develop a sense of what goes into the construction of knowledge in science, of what science can do and what it cannot, of why some findings about some ideas might be worth believing, even if they are inconvenient or go against common sense. It is an important area for further work in Physics Education Research to study how epistemological progress in introductory physics might affect later experience [88, 89].

Reflecting on ourselves personally, we believe that having a sense of how evidence supports results has helped us understand what has taken place over these past two years. It helped us understand why the views kept changing over how COVID-19 is transmitted, as well as why the findings are very unlikely to change over the safety of the vaccines and their efficacy for known variants. It helped us as consumers of advice over whether and when to wear masks, get vaccinated, wash our hands, eat at restaurants, although none of us is specifically trained in bioscience. In fact, one of us hesitated: None of the vaccines had been tested on pregnant women and so there was a dearth of evidence for its effectiveness or potential side effects. This level of uncertainty was sufficient to necessitate a pause, to seek information from respected authorities, consider the impacts of other vaccines on pregnancy, dig into the biological mechanism, and ultimately make a decision to get vaccinated. As well, having a sense of how science works and what it does helped us think of these questions as matters of science rather than of politics. Of course, at other times, it helped us consider the limits of what science can offer.

We wonder if studying science might have broader benefits for post-truth, in particular in what one learns about knowing. It is salient in physics: Ideas that seem to be true, even obvious, even necessary, even believed for centuries by millions of people, may ultimately prove to need revision. It seemed obvious the Earth isn't moving, that objects will stop moving if you stop pushing them, and so on and so on. Doing science well involves humility; students and scientists get used to the phenomenon of being wrong. Perhaps there is a potential for this to help with thinking beyond what is specifically science: Arguments about structural and systemic racism are, in part, arguments to challenge old, automatic, "obvious" thinking.

Still, there is evidence that having learned humility at the lab bench doesn't necessarily transfer to humility about one's views in politics or pedagogy. Physics educators have been arguing for shifts in priority toward students doing science for more than 100 years [90, 91]. But traditional pedagogy remains in place, supported by what seems obvious: that it is essential students learn the canon of established knowledge, as evidenced by their solving problems correctly; that explaining causes learning; that educators should assess students' progress "objectively," such as by standardized exams; that students feeling confused is a problem to avoid during instruction, and to punish on an exam.

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Biographical Sketches

Alberto Stefanel has been a researcher at the University of Udine since 2009, following a twenty-year career as high school mathematics & physics teacher. From December 2015 to 2021, he was the Director of the Centro Interdipartimentale di Ricerca Didattica (InterDepartmental Center for Educational Research) at the University of Udine. His research activity is documented in more than 300 works on the following topics: teaching and learning modern physics in high school; cognitive studies on the role of informal learning environments and hands-on/minds-on activities in activating learning process of primary school pupils on thermal states and processes, electromagnetism, mechanical phenomena, sound, energy; role of ICT in Physics education; studies on teacher preparation and training on educational innovation; role of web environments for physics learning both in university teaching and in teacher training.

Anna McLean Phillips began her career in science education as a secondary school teacher. She later completed her PhD in Physics Education Research at Tufts University. Her dissertation focused on problematizing, the process of refining areas of uncertainties into clear questions and problems, in professional physics and K-16 classrooms. She then completed a post-doctoral research position with the Physics Education Research Lab at Cornell University, studying students' engagement and problematizing in undergraduate instructional laboratories. She returned to Tufts as a post-doctoral researcher and instructor, where she has begun work studying how students engage in the practices of physics within computational physics courses.

Dagmara Sokołowska (PhD) is an adjunct at the Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University. She is involved in physics/science education research in Inquiry-based Learning and Practitioner Inquiry at all levels of schooling - from primary to higher education. She participated in the following EU projects on education: Fibonacci, SECURE, SAILS (7^{th} FP); 3DIPhE, STAMPEd, RISE (ERASMUS+); Akademickie Centrum Kreatywności, Wiking, Feniks (EU Structural Funds). She has been a member of GIREP vzw (International Research Group on Physics Teaching) Board since 2014. She is the author of the National Contest in Science for K1-K8 (Swietlik, eng. *Firefly*) in Poland.

David Hammer has been a professor in Physics Education research (PER) for 30 years. He started in Education at Tufts in 1992, moved in 1998 to join Joe Redish in Physics at the University of Maryland, with a joint appointment in Curriculum & Instruction, and then in 2010 returned to Tufts where he is now Professor of Education with a secondary appointment in Physics & Astronomy. For much of his time since 2010 he served as chair of the Department of Education. At the end of 2018, he began as director of the Tufts Institute for Research on Learning and Instruction, following a gift from the McDonnell Family Foundation.

David R. Sokoloff is Professor of Physics, Emeritus at the University of Oregon. He earned his BA at Queens College of the City University of New York and his PhD in AMO Physics at the Massachusetts Institute of Technology. For over three decades, he has studied students' conceptual understandings, and developed active learning approaches (with NSF and FIPSE support). These include *Interactive Lecture Demonstrations (ILDs)* and *RealTime Physics: Active Learning Laboratories (RTP),* both co-authored by Priscilla Laws and Ronald Thornton.

His work has been published in the *American Journal of Physics*, the *European Journal of Physics*, *Physical Review—Physics Education Research* and *The Physics Teacher*. He has conducted numerous international and national workshops for secondary and university faculty. Since 2004, he has been part of the UNESCO Active Learning in Optics and Photonics (ALOP) team, presenting workshops in more than 30 countries in Africa, Asia and Latin America. He was awarded the 2010 APS Excellence in Physics Education Award (with Priscilla Laws and Ronald Thornton), the 2011 SPIE Educator Award (with the ALOP team), the AAPT Millikan Medal (2007) and Oersted Medal (2020), and the 2020 GIREP Medal. He has been a Fulbright Specialist in Argentina (2011) and Japan (2018), a member of IUPAP Commission 14, and was elected to AAPT's Presidential Chain (2009-2012).

Dena Izadi is a senior research associate in the physics education research lab at Michigan State University. She holds a PhD in experimental biophysics. Izadi's work is focused on using qualitative methods in characterizing the landscape of physics public engagement across the United States. Her primary research interests are creating evidence-based assessment tools and designing and conducting qualitative research practices for equitable and accessible education. Izadi is also passionate about creating hybrid spaces for blending physics with other disciplines, including art and design, to make physics more inviting to non-physicists and the general public.

Eilish McLoughlin is an Associate Professor at the School of Physical Sciences, she holds a PhD in Surface Physics from Dublin City University and is a fellow of the Institute of Physics. She was co-founder of the Research Centre for the Advancement of STEM Teaching and Learning (CASTeL) at Dublin City University and served as Director from 2008-2021. Her interests focus on physics and science education research at all levels of education. She has led and collaborated in a wide range of research projects at European, national, and local level that examine the development of teacher education, curriculum and assessment strategies that adopt integrated STEM and active learning approaches. She was awarded the Institute of Physics Lise Meitner Medal for widening public engagement and education in physics in 2019. She was also honored in 2019 by Science Foundation Ireland for her Outstanding Contribution to STEM Communication. She has served as Chair/co-Chair of IOP Ireland Education group since 2006, as member of IUPAP C14 Commission for Physics Education 2014-2021 and as Executive Secretary of GIREP since 2020.

Elizabeth J. Angstmann, Associate Professor, has been first year director in the School of Physics at the University of New South Wales, Australia, since 2011. She is responsible for the education of thousands of students each year. Prior to this, she obtained her PhD in theoretical atomic physics but decided to focus her career on education and obtained a master's degree in teaching. Her educational background and experience as a high school teacher underpin her use of sound pedagogical bases in her courses. She has an interest in the appropriate use of technology in education and active learning methods. Elizabeth has focused on expanding physics education at the University of New South Wales, introducing both new subjects and degrees. In 2018, she launched an online graduate certificate in physics for science teachers. This exemplifies her passion for assisting schoolteachers to provide the best possible physics experience for their students. Elizabeth is the current Chair of Physics Education Group of the Australian Institute of Physics. Her work has been recognized through an Australian Award for University Teaching citation in 2018 and the prestigious Australian Institute of Physics Education Medal in 2020.

Eugenia Etkina is a Distinguished Professor at Rutgers, the State University of New Jersey. She holds a PhD in physics education from Moscow State Pedagogical University and is a Recipient of the 2014 Millikan Medal of the American Association of Physics Teachers, awarded to educators who have made significant contributions to physics teaching. Professor Etkina designed and coordinated one of the largest physics teacher preparation programs in the United States. She runs professional development for high school and university physics instructors (over 150 workshops since 2000) and contributes to reforms in undergraduate physics courses. Her research is on students learning physics and physics teacher knowledge, in which she has over 100 peer-refereed articles. In 1993, she developed a system, now called the Investigative Science Learning Environment (ISLE) approach, in which students learn physics using processes that mirror scientific practice. The ISLE approach can be used in a physics course of any level (from middle school to graduate coursework). It serves as the basis for the textbook “College Physics: Explore and Apply” and supporting Active Learning Guide and Instructor Guide that are used in many universities and high schools all over the world.

Ileana María Greca is a Full Professor of Specific Didactics at the Universidad de Burgos (Spain), with a PhD in physics teaching (2000), from the Federal University of Rio Grande do Sul (Brazil). Her main research interests are improving science teaching using psychological, epistemological and didactic frameworks and introducing modern physics topics for secondary and high school students. She has recently focused on the epistemological aspects of simulations; integrated STEM/STEAM approaches for comprehensive student competency development and science teachers’ professional development. She has participated in more than 30 competitive research projects (regional, national, and European) as the principal researcher in 13 of them; and has more than 90 articles published in national and international journals indexed in JCR, SCOPUS, and SCIELO; more than 23 book chapters and 3 books.

Irene Arriassecq has a PhD in Science Teaching from the University of Burgos, Spain; M. Sc. in Epistemology and Methodology of Science from the National University of Mar del Plata, Argentina and Professor in Mathematics and Physics from the National University of the Center of the Province of Bs. As., Argentina (UNICEN). She is a CONICET Independent Researcher. Full Professor in the area of Epistemology and History of Science in the Department of Teacher Training of the Faculty of Exact Sciences at UNICEN, in undergraduate and postgraduate degrees. She has also given courses, workshops, seminars and conferences at various national and foreign universities. She is currently the Director of the Center for Education in Sciences with Technologies (ECienTec) belonging to UNICEN and associated with the Scientific Research Commission of the Province of Buenos Aires. At ECienTec, she chairs the line “Teaching contemporary physics topics in secondary school: contributions from and to the nature of science”. She is the author of a book, book chapters and research articles in various reference journals in the area of Science Teaching. In the Association of Physics Teachers of Argentina, she is the Local Secretary for the city of Tandil and a member of the Board of Directors.

Jaume Ametller is a Serra Húnter Associate Professor of Science Education at the University of Girona. He studied Physics at the Autonomous University of Barcelona where he later completed an MA and a PhD in science education. He has been a full-time researcher and a lecturer of science education at the University of Leeds and a post-doctoral fellow at the University of Hokkaido. He is interested in the design of teaching sequences and materials for physics education, the role of communication and dialogue in the construction of knowledge, and how theory informs our understanding of how people learn, particularly in contexts with digital networked tools.

Jenaro Guisasola received his BS in Physics and an MS in Theoretical Physics, both from the University of Barcelona, as well as a PhD in Applied Physics from the University of the Basque Country. He is Assistant Professor of Physics at the University of Basque Country Applied Physics Department. Since 2008, he has also taught Physics Education on the Initial Training of Secondary Science Teachers MA course. His research interest follows two interwoven paths: (1) How Design Based Research can promote instructional models and enhance learning in science curriculum topics. Supported by several grants from Spanish and European projects, this research has given rise to new knowledge about the design of materials and teaching strategies. (2) The use of history and philosophy of science as tools to help organize teaching and learning in science curricula. The agenda includes understanding of the development of scientific knowledge to apply it to science classrooms. He has given numerous invited talks on his research at national and international meetings and conferences. He leads Physics Education Research at University (PERU) for the GIREP thematic group. He is member-elect of the Spanish Royal Physics Society Committee of Physics Education.

Knut Neumann is Director of the Department of Physics Education at the IPN – Leibniz Institute for Science and Mathematics Education and Professor of Physics Education at the Christian-Albrechts- University of Kiel. His research interests include how to assess student competence and the development of student competence in science at various levels of education, how to support students in developing such competence and how to provide teachers with the professional competence, in particular the pedagogical content knowledge (PCK), to best support students in developing competence in science. Dr. Neumann studied mathematics and physics for the teaching profession at the University of Düsseldorf and holds a PhD from the University of Education at Heidelberg.

Kristina Zuza is a lecturer in the Applied Physics department of the University of the Basque Country (UPV/EHU). She graduated in Physics (specializing in Astrophysics) from the University of La Laguna (Canary Islands, Spain) and she got her PhD in Physics Education from the University of the Basque Country. She developed her dissertation about Teaching and Learning Electromagnetic Induction within the A level Research Group (Basque Government) DoPER (DOnostia Physics Eduction Research) led by Jenaro Guisasola where she works to this day. Her research has different interest points. She studies students' difficulties understanding physics laws and concepts and the design, implementation and evaluation of Teaching Learning Sequences at university level. On the other hand, she is interested in the relationship between the general theories on education and discipline-based research needs. She has co-supervised two PhD theses. She is involved in national and European projects and she has several publications in journals like Physical Review-Physics Education Research, American Journal of Physics, European Journal of Physics, Revista Brasileira de Ensino de Fisica, International Journal of Science Education and Enseñanza de las Ciencias.

Lane Seeley earned his Ph.D. in experimental condensed matter physics at the University of Washington. His doctoral work focused on testing microscopic and mesoscopic models for phase changes in the nucleation of ice from liquid water. Since joining the faculty at Seattle Pacific University in 2001, he has worked closely with colleagues to build a close-knit physics department that is primarily focused on student learning. Lane has worked with departmental colleagues on several grant-funded projects aimed at supporting K-12 physics and physical science teachers. He has played an active role in the development of web based diagnostic tools for physical science teachers. Most recently, Lane has been a lead researcher on the SPU Energy Project, a research effort aimed at studying and supporting energy learning among K-12 teachers. Lane's current research interests include building bridges between the energy we learn about and the energy we care about, studying growth in learner's ability and disposition to use a rigorous energy model creatively and flexibly, understanding some of the real and perceived obstacles to student-centered science instruction. Lane is currently serving as a co-PI on an NSF funded Energy and Equity project which aims to address barriers to inclusion and equity at the core of our discipline. We are searching for ways to re-frame and re-prioritize energy learning so that it is more accessible and culturally relevant for all students and particularly for students who do not see their ideas and priorities reflected in our disciplinary cannon.

Laurie McNeil is the Bernard Gray Distinguished Professor in the Department of Physics and Astronomy at the University of North Carolina at Chapel Hill. She earned an AB degree in Chemistry and Physics from Radcliffe College, Harvard University, and a PhD in Physics from the University of Illinois at Urbana-Champaign. After two years as an IBM Postdoctoral Fellow at MIT she joined the faculty at UNC-CH in 1984. She serves as a Deputy Editor at the Journal of Applied Physics. Prof. McNeil is a materials physicist who uses optical spectroscopy to investigate the properties of semiconductors and insulators. She is a Fellow of the American Physical Society and has worked throughout her career to enhance the representation and success of women in physics. She served as co-chair of the Joint Task Force on Undergraduate Physics Programs, a group convened by the American Association of Physics Teachers and the American Physical Society that produced the report, *Phys21: Preparing Physics Students for 21st Century Careers*.

Manjula Sharma completed her early studies at the University of the South Pacific followed by a PhD in physical optics and MEd research methods at The University of Sydney. She is a Professor of Science Education at The University of Sydney, Director of the STEM Teacher Enrichment Academy and Heads the Sydney University Physics Education Research (SUPER) group. She is serving as Vice Chair of IUPAP Commission C14 on Physics Education. Nationally, she has led several substantive government-funded projects such as the Science and Mathematics network of Australian University Educators, SaMnet; and Advancing Science and Engineering through Laboratory Learning, ASELL Schools. Professor Sharma co-founded the premier Australian Conference on Science and Mathematics Education (ACSME) and the International Journal of Innovation in Science and Mathematics Education (IJISME). She has over 100 peer-reviewed publications and has supervised influential PhD students. The findings from her work are being translated into practice and informing decisions. As a change agent, she invests in professional learning and building capacity in science and mathematics education across sectors - universities and schools. Her work is recognized internationally through research partnerships, service on expert/advisory panels, editorial boards and conference committees. Her awards include the 2012 Australian Institute for Physics Education Medal, 2013 OLT National Teaching Fellowship and she is a Principal Fellow of the Higher Education Academy, UK.

Marisa Michelini is a full time Professor of Physics Education in the Department of DMIF at the University of Udine, where she has been Rector Delegate from 1994 for different areas and now for GEO University Consortium, head since 2014. She is responsible of the Physics Education Research Unit (URDF) that she founded in 1992. She is head of the IDIFO project series of PLS on Innovation in Physics Education involving 20 Italian universities from 2006, and ran 6 biannual national Masters for teacher education, 8 full immersion summer schools for talented students and 6 full immersion teacher education schools at national level. Internationally, she has been President of the International Research Group on Physics Education (GIREP) since 2012, board member of the PED Section of the European Physical

Society (EPS) since 2016, board member of Multimedia Physics Teaching Learning (MPTL) since 2014, consultant for CERN- Education since 2019. Her research activity is focused on electrical transport properties of thin films (1985-2000) and physics education research carried out continuously throughout her career on the following lines of research: A) innovative physics education paths on modern physics and prototypes for lab experiments; B) research and development on multimedia; C) initial and professional development of teachers on classical and modern physics, and guidance; D) models of collaboration between school and university: E) informal education: development of an exhibition of 650 hands-on experiments; F) problem solving test (PSO method); G) computer based interactive environments for learning and BYOD; H) learning progression and building of formal thinking in science education base. Internationally, she was the principal investigator on two EU Projects and responsible of the Italian Unit for 5 other EU Projects, 32 national projects and 15 Regional projects in physics education research. She received two main Awards: a) 1989 Italian Physical Society Award for the Exhibit Games Experiments Ideas; b) 2018 IUPAP-ICPE international award for the research in physics education. Her research activity is documented by 620 peer review selected publications in books or journals.

Melanie Keller started her journey in empirical educational research after obtaining her diploma in astrophysics in 2007. This began by researching secondary school physics teachers' enthusiasm in a cross-national study as part of her PhD, which she finished in 2011. Afterwards, she toured several German and Austrian universities and now works as a PostDoc at IPN – Leibniz Institute for Science and Mathematics Education in Kiel, Germany. In her research, she focuses on the role of emotions in teaching and learning and the communication of science.

Mieke De Cock studied physics at KU Leuven (Belgium) where she also obtained her PhD in Theoretical Physics. After her PhD, she worked for a few years as a medical physicist at the Radiotherapy Department in the University Hospital Brussels. In 2007, Mieke returned to KU Leuven where she is now a full professor in the Department of Physics and Astronomy. She is responsible for the Teacher Education Program in Science and Technology and leads the APER (Astronomy and Physics Education Research) group. Her research has a strong focus on conceptual understanding in Physics and Astronomy and on the mathematics-physics interplay, both at secondary and university level.

Michael Bennett is the Director of Education and Workforce Development at the Q-SEnSE NSF Quantum Leap Challenge Institute. Currently, he directs education efforts across the distributed Q-SEnSE institutions to create a comprehensive workforce development landscape that will produce a diverse and skilled quantum workforce. Prior to Q-SEnSE, Dr. Bennett served as the JILA NSF Physics Frontier Center Director of Public Engagement and a Research Associate at the University of Colorado Boulder, leading the University's flagship informal physics education program and studying aspects of instructor pedagogy in informal spaces. He is a member of the American Physical Society and the American Association of Physics Teachers and is involved in both communities.

Mojca Čepič trained as a physics teacher. After graduating, she worked as a high school physics teacher for a few years. She did her PhD in theoretical studies on soft matter, on liquid crystals, focusing on the theory of polar smectics. She proposed the phenomenological model of antiferroelectric liquid crystals, which led to predicting the structure of one of the liquid crystalline phases. The structure was confirmed a few years after her prediction when the resonant X-ray scattering method was developed, which is sensitive not only to the position but also to the orientation of the molecules. She is still active in theoretical research into soft matter. After completing her PhD, she worked as an Assistant Professor of Physics at the University of Ljubljana, Faculty of Education, Department of Physics and Technology. Since her audience consisted of prospective physics teachers, she also became active in research on physics education. She mainly focused on introducing contemporary physics to different levels of education, from superconductivity to liquid crystals and polymers. In addition, she also drew inspiration from everyday phenomena and observations. She developed models to enable controlled studies of circumstances in which phenomena occur such as a double or spreading shadow, an artificial solar eclipse, or underwater rays. She is currently editor-in-chief of the European Journal of Physics, that publishes articles on university physics education.

Natasha G. Holmes is the Ann S. Bowers assistant professor in the Department of Physics at Cornell University with the Laboratory of Atomic and Solid-State Physics. She received her undergraduate degree in physics from the University of Guelph and her master's and PhD in physics at the University of British Columbia. She completed her postdoctoral work at Stanford University with Carl Wieman. Her research focuses on studying the educational impacts of hands-on physics laboratory experiences, exploring student learning and skills development, their attitudes and perceptions of experimental physics, and issues of equity. Her group aims to develop a rigorous evidence base for understanding and improving physics lab instruction.

Nathan Lima has a PhD in Physics Education. He is an associate professor at the Physics Department and the Graduate Program on Physics Education of Federal University of Rio Grande do Sul (Brazil), where he researches History, Philosophy and Science Teaching (HP&ST). His main interests have recently focused on the history of Quantum Theory and implications for Physics Education. He is also an assistant editor at the HPS&ST Newsletter and associate editor at Caderno Brasileiro de Ensino de Física, a Brazilian journal on Physics Education.

Noah Finkelstein is a Professor and Vice Chair in the department of Physics at the University of Colorado, Boulder. He conducts research into physics education, specifically studying the conditions that support students' identities, engagement and outcomes in physics – developing context models. In parallel, he conducts research on how educational transformations get taken up, spread, and sustained. He is a PI in the Physics Education Research (PER) group and was founding co-director of CU's Center for STEM Learning. He co-directs the national Network of STEM Education Centers, is building the STEM DBER-Alliance, and coalitions advancing undergraduate education transformation. He is involved in education policy serving on many national boards, sits on a National Academies' STEM education roundtable, is a Trustee of the Higher Learning Commission, is a Fellow of the American Physical Society, and a Presidential Teaching Scholar and the inaugural Timmerhaus Teaching Ambassador for the University of Colorado system.

Paula R.L. Heron is a Professor of Physics at the University of Washington. She holds a PhD in physics from the University of Western Ontario. Dr. Heron's research focuses on the development of conceptual understanding and reasoning skills. She has given numerous invited talks at international meetings and in university science departments. Dr. Heron is co-Founder and co-Chair of the biannual "Foundations and Frontiers in Physics Education Research" conference series, the premier venue for physics education researchers in North America. She has held leadership roles in the American Physical Society (APS), the American Association of Physics Teachers (AAPT), and the European Physics Education Research Group (GIREP). She served on the National Research Council committee on the status and outlook for undergraduate physics education and co-chaired an APS/AAPT joint task force that produced the report *Phys21: Preparing Physics Students for 21st Century Careers*. She also serves as Associate Editor of *Physical Review – PER*. She is a Fellow of the APS and a co-recipient of the APS Education award with colleagues Peter Shaffer and Lillian McDermott. Dr. Heron is a co-author on the upcoming 2nd Edition of *Tutorials in Introductory Physics,* a set of that has widely used and influential instructional materials.

Ricardo Karam is an associate professor at the Department of Science Education of the University of Copenhagen and the leader of its research group on Didactics of Physics. He holds a PhD in Physics Education from the University of São Paulo (Brazil) and was a postdoctoral fellow of the Humboldt foundation at the universities of Hamburg, Dresden and Helsinki. His research interests include the educational implications of the relationship between physics and mathematics and the pedagogic value of the history of physics for the teaching/learning of physics concepts.

Stamatis Vokos, an APS Fellow, investigates cognitive and affective aspects of teaching and learning in physics, supporting systemic change efforts at the local, national, and international levels. He has served on multiple committees of APS and AAPT and has chaired the National Task Force on Teacher Education in Physics. He is currently professor of physics at California Polytechnic State University in San Luis Obispo, where he also directs the STEM Teacher and Researcher program. As part of the Physics Education Group at the University of Washington from 1994 to 2002, Vokos contributed to the research and curriculum development efforts of the Group, and played a leadership role in its local, regional, and statewide teacher education efforts. At Seattle Pacific University from 2002 until 2016, he was instrumental in the recruitment one of the most prolific groups of physics education researchers in the United States. In the last two dozen years, he has collaborated with scores of senior and junior researchers, having done some of his most treasured work over the years with his co-authors on this chapter, Eugenia Etkina and Lane Seeley.

Stefan Sorge is a postdoctoral researcher at the Department of Physics Education at the IPN – Leibniz-Institute for Science and Mathematics Education in Kiel, Germany. After graduating from Martin-Luther University Halle-Wittenberg with the first state examination for mathematics and physics teachers in 2014, he went to the IPN to pursue a PhD in physics education. His research focus is on the development of pre-service and in-service physics teachers' professional competence.