Preprint —to appear in J. Guisasola & E. McLoughlin (Eds) *Connecting Research in Physics Education with Teacher Education 3*. International Commission of Physics Education.

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 been based almost entirely on 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, 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. It was the data that was 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 one knows for sure.

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 truth 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 constructs 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 constructed 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 Constructed 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 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 how 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 the- oretical 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, describes how 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, depending on the nature of the phenomena, and are connected deeply with the theoretical 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 constructing 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 perceptions of physics as authority-driven is certainly not what physicists aspire to, and they are in conflict with disciplinary values of pushing boundaries and seeking inconsistencies in theory. Although Fermi's theory of neutrinos did not fit with the current day understandings of particles, 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. That is certainly within the values and practices of physics, to rely on others' expertise, 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 construct, 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 might happen, that shift. 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, and 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 on how 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 con- sider 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 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 publish- able 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: 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 construct, assess, and revise what to accept as true, by attending, interpreting, and responding to arguments and counter- argument, 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 counter- productive epistemologies [79–82], 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 the 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 truths 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 exams.

Acknowledgement

This work was supported in part by the U.S. National Science Foundation, Grants DUE 2000739 and 2000394.

References

[1] Oxford Languages. Word of the year 2016. (2016). URL https://languages.oup. com/word-of-the-year/2016/.

[2] Chinn, C. A., Barzilai, S., & Duncan, R. G. (2020). Disagreeing about how to know: The instructional value of explorations into knowing. *Educational Psychologist*, *55*(3), 167-180
[3] Kienhues, D., Jucks, R., & Bromme, R. (2020). Sealing the gateways for post-truthism: Reestablishing the epistemic authority of science. *Educational Psychologist*, *55*(3), 144-154.
[4] Jiménez-Aleixandre, M. P., Bugallo Rodríguez, A., & Duschl, R. A. (2000). "Doing the lesson" or "doing science": Argument in high school genetics. *Science education*, *84*(6), 757-792.
[5] Hammer, D. (1994). Epistemological beliefs in introductory physics. *Cognition and instruction*, *12*(2), 151-183.
[6] Sabra, A. I. (2003) Ibn al-Haytham: Brief life of an Arab mathematician. *Harvard Magazine*, September-October, 54–55.
[7] Appiah, K. A. (2018). *The Lies that Bind: Rethinking identity*. Profile Books.
[8] Feinstein, N. W., & Waddington, D. I. (2020). Individual truth judgments or purposeful, collective sensemaking? Rethinking science education's response to the post-truth era. *Educational Psychologist*, *55*(3), 155-166.
[9] Kuhn, T. (2021). *The structure of scientific revolutions* (pp. 176-177). Princeton University Press.
[10] Popper, K. (2013). *All life is problem solving*. Routledge.
[11] Phillips, A. M., Watkins, J., & Hammer, D. (2017). Problematizing as a scientific endeavor. *Physical Review Physics Education Research*, *13*(2), 020107.
[12] Cartwright, N. (1999). *The dappled world: A study of the boundaries of science*. Cambridge University Press.
[13] Bilenky, S. M. (2013). Neutrino. History of a unique particle. *The European Physical Journal H*, *38*(3), 345-404.
[14] Rubin, R. J. (2006) "Vera Cooper Rubin" In Nina Byers and Gary Williams, editors, *Out of the shadows: contributions of twentieth-century women to physics*, Chapter 31, pages 343–354. Cambridge University Press.
[15] Einstein, A., Podolsky, B., & Rosen, N. (1935). Can quantum-mechanical description of physical reality be considered complete?. *Physical review*, *47*(10), 777.
[16] Overbye, D. (2001). *Einstein in Love: A scientific romance*. Penguin Publishing Group.
[17] European Organization for Nuclear Research (CERN) Data Centre (2021).URL https://information-technology.web.cern.ch/sites/information-technology.web.cern.ch/files/CERNDataCentre_KeyInformation_01June2018V1.pdf.
[18] Klitzing, K. V., Dorda, G., & Pepper, M. (1980). New method for high-accuracy determination of the fine-structure constant based on quantized Hall resistance. *Physical review letters*, *45*(6), 494.
[19] Miller, E., Manz, E., Russ, R., Stroupe, D., & Berland, L. (2018). Addressing the epistemic elephant in the room: Epistemic agency and the next generation science standards. *Journal of Research in Science Teaching*, *55*(7), 1053-1075.
[20] Larivière, V., Ni, C., Gingras, Y., Cronin, B., & Sugimoto, C. R. (2013). Bibliometrics: Global gender disparities in science. *Nature News*, *504*(7479), 211.
[21] Witteman, H. O., Hendricks, M., Straus, S., & Tannenbaum, C. (2019). Are gender gaps due to evaluations of the applicant or the science? A natural experiment at a national funding agency. *The Lancet*, *393*(10171), 531-540.
[22] Eaton, A. A., Saunders, J. F., Jacobson, R. K., & West, K. (2020). How gender and race stereotypes impact the advancement of scholars in STEM: Professors' biased evaluations of physics and biology post-doctoral candidates. *Sex Roles*, *82*(3), 127-141.
[23] Akos, P., & Kretchmar, J. (2016). Gender and ethnic bias in letters of recommendation: considerations for school counselors. *Professional School Counseling*, *20*(1), 1096-2409.
[24] Sprague, J., & Massoni, K. (2005). Student evaluations and gendered expectations: What we can't count can hurt us. *Sex Roles*, *53*(11), 779-793.
[25] Potvin, G., & Hazari, Z. (2016). Student evaluations of physics teachers: On the stability and persistence of gender bias. *Physical Review Physics Education Research*, *12*(2), 020107.
[26] Potvin, G., Hazari, Z., Tai, R. H., & Sadler, P. M. (2009). Unraveling bias from student evaluations of their high school science teachers. *Science Education*, *93*(5), 827-845.
[27] Fan, Y., Shepherd, L. J., Slavich, E., Waters, D., Stone, M., Abel, R., & Johnston, E. L. (2019). Gender and cultural bias in student evaluations: Why representation matters. *PloS one*, *14*(2), e0209749.
[28] Kreitzer, R. J., & Sweet-Cushman, J. (2021). Evaluating student evaluations of teaching: A review of measurement and equity bias in SETs and recommendations for ethical reform. *Journal of Academic Ethics*, 1-12.
[29] Matz, R. L., Koester, B. P., Fiorini, S., Grom, G., Shepard, L., Stangor, C. G., ... & McKay, T. A. (2017). Patterns of gendered performance differences in large introductory courses at five research universities. *AERA Open*, *3*(4), 2332858417743754.
[30] Quinn, D. M. (2020). Experimental evidence on teachers' racial bias in student evaluation: The role of grading scales. *Educational Evaluation and Policy Analysis*, *42*(3), 375-392.

[31] Schuster, C., Narciss, S., & Bilz, J. (2021). Well done (for someone of your gender)! Experimental evidence of teachers' stereotype-based shifting standards for test grading and elaborated feedback. *Social Psychology of Education*, 1-26.
[32] Bonefeld, M., & Dickhäuser, O. (2018). (Biased) grading of students' performance: Students' names, performance level, and implicit attitudes. *Frontiers in psychology*, *9*, 481.
[33] Krawczyk, M. (2018). Do gender and physical attractiveness affect college grades?. *Assessment & Evaluation in Higher Education*, *43*(1), 151-161.
[34] Hinnerich, B. T., Höglin, E., & Johannesson, M. (2015). Discrimination against students with foreign backgrounds: Evidence from grading in Swedish public high schools. *Education Economics*, *23*(6), 660-676.
[35] Malouff, J. M., & Thorsteinsson, E. B. (2016). Bias in grading: A meta-analysis of experimental research findings. *Australian Journal of Education*, *60*(3), 245-256.
[36] Hofer, S. I. (2015). Studying gender bias in physics grading: The role of teaching experience and country. *International Journal of Science Education*, *37*(17), 2879-2905.
[37] Dasgupta, N. (2011). Ingroup experts and peers as social vaccines who inoculate the self-concept: The stereotype inoculation model. *Psychological Inquiry*, *22*(4), 231-246.
[38] Dennehy, T. C., & Dasgupta, N. (2017). Female peer mentors early in college increase women's positive academic experiences and retention in engineering. *Proceedings of the National Academy of Sciences*, *114*(23), 5964-5969.
[39] Cavicchi, E. (2014). Learning science as explorers: Historical resonances, inventive instruments, evolving community. *Interchange*, *45*(3-4), 185-204.
[40] Kapon, S., Laherto, A., & Levrini, O. (2018). Disciplinary authenticity and personal relevance in school science. *Science Education*, *102*(5), 1077-1106.
[41] Salter, I., & Atkins, L. (2013). Student-generated scientific inquiry for elementary education undergraduates: Course development, outcomes and implications. *Journal of Science Teacher Education*, *24*(1), 157-177.
[42] Barzilai, S., & Chinn, C. A. (2020). A review of educational responses to the "post-truth" condition: Four lenses on "post-truth" problems. *Educational Psychologist*, *55*(3), 107-119.
[43] Holmes, N. G., & Bonn, D. A. (2015). Quantitative comparisons to promote inquiry in the introductory physics lab. *The Physics Teacher*, *53*(6), 352-355.
[44] Smith, E. M., Stein, M. M., & Holmes, N. G. (2020). How expectations of confirmation influence students' experimentation decisions in introductory labs. *Physical Review Physics Education Research*, *16*(1), 010113.
[45] Hammer, D., Elby, A., Scherr, R. E., & Redish, E. F. (2005). Resources, framing, and transfer. In Jose P. Mestre, editor, *Transfer of learning from a modern multidisciplinary perspective*, Chapter 3, pages 89–119. Information Age Publishing, Incorporated, Greenwich, CT.
[46] Hutchison, P., & Hammer, D. (2010). Attending to student epistemological framing in a science classroom. *Science Education*, *94*(3), 506-524.
[47] Eriksson, I., & Lindberg, V. (2016). Enriching 'learning activity' with 'epistemic practices'–enhancing students' epistemic agency and authority. *Nordic Journal of Studies in Educational Policy*, *2016*(1), 32432.
[48] Stroupe, D. (2014). Examining classroom science practice communities: How teachers and students negotiate epistemic agency and learn science-as-practice. *Science Education*, *98*(3), 487-516.
[49] Phillips, A. M., Sundstrom, M., Wu, D. G., & Holmes, N. G. (2021). Not engaging with problems in the lab: Students' navigation of conflicting data and models. *Physical Review Physics Education Research, 17*(2), 020112.
[50] Sundstrom, M., Phillips, A. M, and Holmes, N. G. (2020). Problematizing in inquiry-based labs: how students respond to unexpected results. In Steven Wolf, Michael B. Bennett, and Brian W. Frank, editors, *Physics Education Research Conference 2020*, pages 539–544.
[51] Phillips, A. M., Watkins, J., & Hammer, D. (2018). Beyond "asking questions": Problematizing as a disciplinary activity. *Journal of Research in Science Teaching*, *55*(7), 982-998.
[52] Engle, R. A., & Conant, F. R. (2002). Guiding principles for fostering productive disciplinary engagement: Explaining an emergent argument in a community of learners classroom. *Cognition and instruction*, *20*(4), 399-483.
[53] Holmes, N. G., & Wieman, C. E. (2018). Introductory physics labs: We can do. *Physics Today*, *71*, 1-38.
[54] Berland, L. K., Schwarz, C. V., Krist, C., Kenyon, L., Lo, A. S., & Reiser, B. J. (2016). Epistemologies in practice: Making scientific practices meaningful for students. *Journal of Research in Science Teaching*, *53*(7), 1082-1112.
[55] Ford, M. J. (2015). Educational implications of choosing "practice" to describe science in the next generation science standards. *Science Education*. 99(6), 1041–1048.
[56] Ford, M. (2008). 'Grasp of practice'as a reasoning resource for inquiry and nature of science understanding. *Science & Education*, *17*(2), 147-177.

[57] Séré, M. G., Journeaux, R., & Larcher, C. (1993). Learning the statistical analysis of measurement errors. *International Journal of Science Education*, *15*(4), 427-438.
[58] Allie, S., Buffler, A., Kaunda, L., & Inglis, M. (1997). Writing-intensive physics laboratory reports: Tasks and assessment. *The Physics Teacher*, *35*(7), 399-405.
[59] Manz, E. (2015). Resistance and the development of scientific practice: Designing the mangle into science instruction. *Cognition and Instruction*, *33*(2), 89-124.
[60] Gosling, C. (2021). Authentic Independent Investigations in High School Physics Laboratories. *The Physics Teacher*, *59*(1), 48-50.
[61] Morrison, A. (2014). From cookbooks to single sentences: The evolution of my labs. *The Physics Teacher*, *52*(8), 505-506.
[62] Wells, M., Hestenes, D., & Swackhamer, G. (1995). A modeling method for high school physics instruction. *American journal of physics*, *63*(7), 606-619.
[63] Marasco, D. (2020). Teaching an Old Ball New Tricks: Another Look at Energetics, Motion Detectors, and a Bouncing Rubber Ball. *The Physics Teacher*, *58*(1), 62-63.
[64] Etkina, E., & Van Heuvelen, A. (2007). Investigative science learning environment–A science process approach to learning physics. *Research-based reform of university physics*, *1*(1), 1-48.
[65] Etkina, E., & Planinšič, G. (2015). Defining and developing "critical thinking" through devising and testing multiple explanations of the same phenomenon. *The Physics Teacher*, *53*(7), 432-437.
[66] Blais, B. S. (2020). Model Comparison in the Introductory Physics Laboratory. *The Physics Teacher*, *58*(3), 209-213.
[67] Moore, J. C., & Rubbo, L. J. (2016). Modeling hidden circuits: An authentic research experience in one lab period. *The Physics Teacher*, *54*(7), 423-426.
[68] Siddiqui, S., Zadnik, M., Shapter, J., & Schmidt, L. (2013). An inquiry-based approach to laboratory experiences: Investigating students' ways of active learning. *International Journal of Innovation in Science and Mathematics Education*, *21*(5).
[69] Bartlett, P. A., & Dunnett, K. (2019). Secret objectives: promoting inquiry and tackling preconceptions in teaching laboratories. *arXiv preprint arXiv:1905.07267*.
[70] Dunnett, K., Kristiansson, M. K., Eklund, G., Öström, H., Rydh, A., & Hellberg, F. (2020). Transforming physics laboratory work from'cookbook'type to genuine inquiry. *arXiv preprint arXiv:2004.12831*.
[71] Auchincloss, L. C., Laursen, S. L., Branchaw, J. L., Eagan, K., Graham, M., Hanauer, D. I., ... & Dolan, E. L. (2014). Assessment of course-based undergraduate research experiences: a meeting report.
[72] Ballen, C. J., Thompson, S. K., Blum, J. E., Newstrom, N. P., & Cotner, S. (2018). Discovery and broad relevance may be insignificant components of course-based undergraduate research experiences (CUREs) for non-biology majors. *Journal of microbiology & biology education*, *19*(2), 19-2.
[73] Rowland, S., Pedwell, R., Lawrie, G., Lovie-Toon, J., & Hung, Y. (2016). Do we need to design course-based undergraduate research experiences for authenticity?. *CBE—Life Sciences Education*, *15*(4), ar79.
[74] Holmes, N. G., & Wieman, C. E. (2016). Examining and contrasting the cognitive activities engaged in undergraduate research experiences and lab courses. *Physical Review Physics Education Research*, *12*(2), 020103.
[75] Elby, A. (2019). Did the Framework for K-12 Science Education trample itself? A reply to``Addressing the epistemic elephant in the room: Epistemic agency and the next generation science standards''. *Journal of Research in Science Teaching*, *56*(4), 518-520.
[76] Damşa, C. I., Kirschner, P. A., Andriessen, J. E., Erkens, G., & Sins, P. H. (2010). Shared epistemic agency: An empirical study of an emergent construct. *The Journal of the Learning Sciences*, *19*(2), 143-186.
[77] Erduran, Sibel, and María Pilar Jiménez-Aleixandre. "Argumentation in science education." *Perspectives from classroom-Based Research. Dordre-cht: Springer* (2008).
[78] Bang, M., & Medin, D. (2010). Cultural processes in science education: Supporting the navigation of multiple epistemologies. *Science education*, *94*(6), 1008-1026.
[79] Adams, W. K., Perkins, K. K., Podolefsky, N. S., Dubson, M., Finkelstein, N. D., & Wieman, C. E. (2006). New instrument for measuring student beliefs about physics and learning physics: The Colorado Learning Attitudes about Science Survey. *Physical review special topics-physics education research*, *2*(1), 010101.
[80] Prosser, M., Walker, P., & Millar, R. (1996). Differences in students' perceptions of learning physics. *Physics Education*, *31*(1), 43.
[81] Redish, E. F., Saul, J. M., & Steinberg, R. N. (1998). Student expectations in introductory physics. *American journal of physics*, *66*(3), 212-224.
[82] Trigwell, K., Prosser, M., & Waterhouse, F. (1999). Relations between teachers' approaches to teaching and students' approaches to learning. *Higher education*, *37*(1), 57-70.

[83] Holmes, N. G., Olsen, J., Thomas, J. L., & Wieman, C. E. (2017). Value added or misattributed? A multi-institution study on the educational benefit of labs for reinforcing physics content. *Physical Review Physics Education Research*, *13*(1), 010129.
[84] Redish, E. F., & Hammer, D. (2009). Reinventing college physics for biologists: Explicating an epistemological curriculum. *American Journal of Physics*, *77*(7), 629-642.
[85] Madsen, A., McKagan, S. B., & Sayre, E. C. (2015). How physics instruction impacts students' beliefs about learning physics: A meta-analysis of 24 studies. *Physical Review Special Topics-Physics Education Research*, *11*(1), 010115.
[86] Keller, E. F. (2002). *Making sense of life*. Harvard University Press.
[87] Irzik, G., & Nola, R. (2011). A family resemblance approach to the nature of science for science education. *Science & Education*, *20*(7), 591-607.
[88] Gouvea, J., Sawtelle, V., & Nair, A. (2019). Epistemological progress in physics and its impact on biology. *Physical Review Physics Education Research*, *15*(1), 010107.
[89] Radoff, J., Jaber, L. Z., & Hammer, D. (2019). "It's scary but it's also exciting": Evidence of meta-affective learning in science. *Cognition and Instruction*, *37*(1), 73-92.
[90] Otero, V. K., & Meltzer, D. E. (2016). 100 years of attempts to transform physics education. *The Physics Teacher*, *54*(9), 523-527.
[91] Meltzer, D. E., & Otero, V. K. (2015). A brief history of physics education in the United States. *American Journal of Physics*, *83*(5), 447-458.