



Learning to become ignorant: Improving the quality of epistemic knowledge in science education

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Abstract

In considering goals for science education, it is conventional to make arguments for the utility of scientific knowledge for a variety of purposes. Less prominent are rationales based on the beauty or truth of science. In this paper, we examine how an approach to science education might be different if we shift the goals of communication to an appreciation of the ways in which our knowledge is limited, and how the practical boundaries of our knowledge can be closer than we think—in other words, *how* we are collectively ignorant. Key to this approach is a renewed understanding of the role of material investigations in providing partial knowledge. Instead of providing incontrovertible evidence, empirical investigations provide a form of “explanatory excess” whereby the appropriate choice of explanation is not necessarily one that can be simplistically determined. Although scientific practices provide techniques to *minimize* the possibility of error in making our conclusions, these practices are performed by fallible human communities, from which the notion of “tentative, yet durable” claims derives. We argue that public scientific literacy may be better served by more circumspect claims of validity, and crucially, an enhanced

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understanding of the ways in which materiality influences epistemic processes and limits our claims. We illustrate these proposals through the case of the International Young Physicists' Tournament, a contest that invites participants to play with interesting physical phenomena for over a year. We identify three factors prominent in these tournament problems that present possibilities for increasing the authenticity of practical investigations. These are (i) multiple physical interactions in phenomena leading to the openness of choice of explanatory theory; (ii) the qualitative, subjective nature of the explanatory utility of theories; and (iii) the material contingency of empirical investigations. We argue that a more open-handed embrace of the limits of our knowledge may serve as a better epistemic orientation for science instruction.

KEYWORDS

boundaries of knowledge, practical investigations, epistemic practices, ignorance, International Young Physicists' Tournament

1 | INTRODUCTION

In conventional approaches to instruction, there is at least an assumption of information asymmetry between instructor and student: instructors are in possession of some knowledge or skill which needs to be communicated to the student, who is in lack. Such an approach ultimately privileges teaching as telling and learning as listening, as efficient methods for instruction. Instead of prioritizing the communication of information as a goal, we propose that a different goal for science education can be the communication and exploration of the variegated boundaries between knowledge and ignorance. More specifically, we propose that science education needs to attend to the ways in which our knowledge is limited in practice; and how in principle, we cannot have arbitrarily perfect knowledge. Attending to ignorance as a goal provides a solution to the problem of appreciating the “tentative, yet durable” nature of science: Why is scientific knowledge tentative, and upon what factors can we have faith in the durability of such knowledge? Especially in the condition of post-truth that we find ourselves in today, such questions are especially pertinent—scientists often find themselves in positions where it is unreasonable to consider anything else but the scientific consensus. Yet, a dogmatic assertion of the correctness of science may not help in convincing nonscientists of the contention at hand.

Scientific claims are socially constructed representations of the behavior of natural systems, for which there is necessarily some latitude in interpretation, despite methodological attempts to minimize such “slippage.” In investigations of physics problems that we focus on in this paper, we assert that beyond an abstract competence in these representations and methodological controls, empirical investigations hold the key to resolving epistemic conflicts. Crucially, however, such a resolution may not necessarily be conclusive, even in principle. We identify three factors that cause empirical investigations to present equivocal support to theoretical claims: (i) multiple physical interactions in phenomena; (ii) qualitative, subjective nature of the explanatory utility of theories; and (iii) material contingencies in empirical investigations.

Considering the educational problem of the practical investigation, we propose that the goal of such investigations *qua* instructional activity should shift from an explicitly pedagogical intention of communicating the inquiry process as an unproblematic series of steps, towards a more open-ended, authentic investigation whose endpoints may not be completely foreseeable in advance. The challenge of practical investigation is the communication of our ignorance and uncertainty at the boundaries of knowledge. While the general equations and theories apply to a wide range of cases, there will be edge cases and interacting effects which will require a variety of approaches to resolution, none of which can be accurately predicted from the outset. Such an approach is necessarily hard to communicate as there are no clear and explicit rules that govern the behavior of such boundary cases and interactions. Instead, practitioners may rely on heuristics and embodied *cultural* practices to interact with the materiality of the situation at hand. While such concepts have been making inroads in disciplines such as science-technology-society studies, science educators have not demonstrated a similar enthusiasm.

We demonstrate these concepts within the context of an international physics tournament, which presents an edge case for science educators. We show that especially for problems that are interesting to physics practitioners, realistic problems do not resemble the typical laboratory investigations used in instructional settings. Indeed, it appears that instructional laboratory activities are so specialized and present such a caricature of practitioner physics that providing them as a student's exclusive experience is a disservice to a more widespread understanding of science. When realistic scientific investigations involving multiple specializations need to be understood by the public, these reductionist experiences do not adequately prepare the nonexpert to appreciate why answers need to be partial, why knowledge shifts, and how social negotiation occurs when knowledge is made. In relation to recent controversies such as the leak of private communications between climate research scientists, the fuller understanding of science that we advocate here would go a long way towards appreciating why there was no perfidy. On the other hand, attempts by purveyors of misinformation seeking to characterize the scientific consensus as unsettled (when in fact it is not) will have a harder time if the general public can acquire a better understanding of the relationship between investigations, evidence, and the epistemic status of such knowledge claims that might emerge.

2 | WHY TEACH SCIENCE?

For science educators, a question that recurs occasionally, but perhaps not often enough, is the purpose of science education. Certainly, as educators, a primary goal for many would be the communication of the various ways in which we perceive science to be useful, true, or beautiful. Science has been perceived to be of high utility in contemporary society, in no small part because of the ways in which we have leveraged our knowledge in many aspects of our lives. The interactions between science and society, generally speaking, has been a concern for science educators (among which we count ourselves). For instance, such interest among researchers has taken the form of concern for bridging the gap between the “two cultures” (Snow, 1959) of sciences and the humanities (Klopfer & Aikenhead, 2022); even earlier, Longbottom and Butler (1999) have made a case that science, as a paragon of rationality among school subjects, should serve as an exemplar for democratic decision-making. More recently, concerns about the corrosive influence of contemporary media on the public trust in science and evidence-backed rational debate have also been a motivating concern (e.g., Höttecke & Allchin, 2020). The interactions between scientific knowledge and the societal outcomes of its differential distribution manifest themselves in a concern that marginalized groups may not be sufficiently represented in the scientific community (e.g., Kang et al., 2019; King & Pringle, 2019; Madkins & McKinney de Royston, 2019). Certainly, few researchers will doubt the economic imperative for science education, and indeed it is more than likely that the utility argument for teaching science as preparation for economic life has been used by many educators and researchers, despite the many serious issues of concern (Donovan et al., 2014; Roschelle et al., 2011). Even though there is diversity in these purposes, what seems common is a desire to communicate some valued knowledge; that if only others knew what



we know, many problems will find a resolution. Yet, fewer arguments exist to promote the value of science for its ability to discern truth (and its limits thereof), and its beauty. In this paper, we seek to address this shortcoming in our public understanding of truth that arises from the notion of science as a unique mechanism for generating truth claims. We assert that conventional school approaches place too much emphasis on the products of inquiry, and not enough on the processes, specifically in the ways in which one might generate *partial or limited* truth claims in response to phenomena. From this perspective, the desire is not necessarily to communicate knowledge and seemingly assert one's power over another, but to express collegiality as a fellow journeyman, acknowledging one's limits yet partaking in the joy of being able to accomplish what we have been able to.

Consider the arguments for scientific literacy, the very idea implying a form of basic knowledge one ought to possess to qualify as "literate." Feinstein (2011) articulates *utility* as a consideration for science educators: while advocates often claim that scientific literacy is important for participation in public life, far too little evidence exists on the relationship between knowledge of scientific literacy components and its presumed positive effects on people. Feinstein (2011) contends instead that an empirical basis for the utility of scientific literacy in everyday lives needs to be developed, and that increased attention needs to be paid to the usefulness of science instruction that might lead people to actually use scientific knowledge and skills in everyday situations. Although Feinstein (2011, p. 169) acknowledges that science instruction may also attend to scientific literacy for its "inherent cultural worth, as well as esthetic and even moral value," he asserts that it is the utility of science in everyday life that is most important. Such a position certainly has been informed by the numerous debates about the role of science (and technology) in contemporary societies. In the face of widespread misinformation about contentious contemporary issues ranging from climate change to vaccine refusal, and more perennial ones such as biological evolution or various human health issues, epistemic issues have risen in importance.

Almost to neatly encapsulate one approach to this matter, Sharon and Baram-Tsabari (2020) suggest that an important component (and function) of scientific literacy should be its ability to correctly inform students and somehow immunize them from scientific misinformation. As with Collins (2009), we are similarly concerned about the balance between skepticism and credulity, specifically how a certain epistemic modernization in the public sphere has led to a situation where "the founding myth of the individual scientist using evidence to stand against the power of the church or state [...] has been replaced with a model in which Machiavellian scientists engage in artful collaboration with the powerful." This essential tension between skepticism and credulity and the notion of the centrality of science education for democratic participation in contemporary societies is certainly not new. Even from the turn of the century Longbottom and Butler (1999) argued that democratic decision-making requires certain rationalism, and that science, being the quintessentially rational school subject, is particularly suited for this purpose, provided that students are insulated from the excesses of both positivism and postmodernism (Allchin, 2004). Collins and Evans (2017) strongly urge their readers of the importance of science in democracies, surveying about a century's worth of thought in science-technology-studies into three broad periods they call waves, corresponding to the extremes of credulity, and skepticism; and a proposed third period describing the current time where we need to deal with the delicate balancing act of accepting the socially constructed nature of knowledge, but the nonetheless nonarbitrary nature of scientific knowledge.

The criticism we propose here is not with the matter of the effectiveness of these potential approaches. Rather, it is with the apparently rational response to dealing with the issues engendered by scientific knowledge, perhaps exemplified by an aphorism such as Asimov's: "If knowledge can create problems, it is not through ignorance that we can solve them." We counter that it is not clear that knowledge will necessarily solve problems. Consider, for instance, genetic testing for hereditary disease: given *probabilistic* information on the likelihood of developing the disease, patients may develop significant distress, or even elect to undergo risky treatments that may provide worse outcomes than simply doing nothing (Burgess, 2001; Schmeler et al., 2006; Tæubner et al., 2018). School science has far too often been presented as truth beyond doubt, and in this respect, we are in accord with recent research efforts at foregrounding ambiguities in science education (Tang et al., 2022), as well as the professional development of teachers to deal with uncertainties in the classroom (Manz & Suárez, 2018).

3 | SCIENCE, AS PRACTICED BY FALLIBLE HUMAN SOCIETIES

Current resources of knowledge may also include systematic blind spots. Contemporary science is expensive to practice, and as such, is amenable to influence by large industrial and economic concerns. The cases of “undone science” (Frickel et al., 2010) demonstrate how political decision-making and scientific knowledge interact. For example, knowledge of the environmental safety of chlorine compounds is biased towards ignorance because of a ground-level assumption of the role of regulation. While regulators are supposed to systematically identify chlorinated chemicals, the prospect of sifting through “tens, perhaps hundreds, of thousands of chlorinated industrial substances, by-products, and breakdown products” (p. 451) presents such a challenge that it results in a science that is essentially undoable. To suppose then that databases of hazardous substances are complete would be problematic. The point of this is not to add to the list of scientific findings, or facts about science, that students are supposed to be able to recite; it is not even to claim that interactions between science and society modify the “ideal” manner by which knowledge is generated, distributed, and used. The problem here has to do with the distinction between what scientists *say* they do, and what they *actually* do (Pickering, 2008)—when we think about science and scientific knowledge, it is still unfortunately the case that we tend to think of its practice as if independent of its societal conditions: that the human foibles are merely contextual distractions that deviate from the ideals of its practice. This is a curriculum problem and one deeply enmeshed in power relations: it can be in scientists' vested interest to be portrayed as knowledgeable and authoritative so as to acquire and retain their social standing. However, there must come a point where educators, following along on this charade, will actually serve to degrade this goal as when scientists are found guilty of misconduct. In our opinion, a better position is one of an open-handed honest acknowledgment of our limitations.

Science is deeply enmeshed in human preferences even while nature serves as a neutral arbiter for our desired outcomes. Even in the physical sciences, examples such as Galileo and Kelvin give us instructive lessons on how the dominant science of its time can be willfully ignorant (Ravetz, 2015). Galileo abided by ancient Stoic doctrines declaring the irrelevance of the attraction of the moon to the tides, producing a theory that only predicted one daily tide (there are actually two). Lord Kelvin, based on his religious preferences, famously declared that there was nothing really new for physics to discover, save two small clouds on the horizon which later turned out to revolutionize the discipline. These “clouds” were the relative motion of massive objects through the aether, and the Maxwell-Boltzmann theorem of the equipartition of energy, which eventually became to be solved by special relativity and quantum mechanics (Passon, 2021). This is also not to say that scientists, in general, engage in forms of wishful thinking, or that science itself is unreliable. However, if we have to continually excuse the behavior of individual scientists or even collectives, at which point do we cross the threshold and acknowledge that the entire scientific venture is problematic, in that there exist entire regions that we are systematically and willfully ignorant of? This ignorance arises in large part due to our attachment to current frameworks of understanding: what begins as a useful heuristic or starting assumption can initially be a productive means to understand, before becoming codified as the correct interpretation, finally limiting alternatives as “unscientific.” That these famous scientists made errors of this form does not necessarily indicate individual failing, but rather points to the notion of what we might term “explanatory excess”: there are almost always more explanations for phenomena than what exists. Crucially, the choice of explanation (theory) is not simplistically determined or even adjudicated by reference to nature. When particular theories have served scientists for a long time, they can be incredibly reluctant to abandon these theories in the face of contradictory evidence, instead inventing hitherto unobserved factors to account for anomalies. In some cases, such as the discovery of Neptune via the prediction that it accounted for the anomalous behavior of Uranus, these procedures worked sensationally. However, in the aberrant behavior of planet Mercury, the invention of the unseen planet Vulcan did not work; relativistic physics had to be invoked to solve the mystery (Becker, 2018). On what grounds do scientists justify adding “epicycles,” “calibration factors,” or completely new theoretical objects is not something that we routinely teach students; neither do we suggest to students that the science they learn is anything but settled.



The problem for educators then is the manner in which we may teach students in such a way as to increase the chances of their transcending the boundaries of knowledge, especially since frameworks for thinking can potentially become constraining. The cases of Galileo and Lord Kelvin are ample practical demonstrations of the phenomenon of motivated reasoning: the “human tendency to selectively “seek, evaluate, evaluate, and recall information” that supports prior beliefs and commitments (Drummond & Fischhoff, 2017, p. 9588). Evidence suggests that it derives from automatic, uncontrolled processes in the human mind, and it requires conscious effort to override their later effects on opinion formation.” Motivated reasoning is the reason why a rational response to the problem of ignorance is unlikely to succeed. Rationally, ignorance is a deficit that simply needs remediation; a student who is ignorant about something should rationally accept the “correct” view. In studies of scientific communication, Simis et al. (2016) point out that this deficit model has been dominant since an influential 1980s model that defined scientific literacy in terms of possession of particular knowledge claims, and found a majority of US adults to be illiterate (Miller, 2004). Significantly, Simis et al. (2016, p. 400) found that “scientists who have less positive attitudes towards the social sciences are more likely to adhere to the knowledge deficit model of science communication.” In other words, a scientific worldview can limit the effectiveness of communication strategies. Humans are not hyperrational individuals who will automatically change their beliefs when informed. Instead, we can and often do exercise the fundamental human quality of refusal.

4 | NATURE IS UNCERTAIN, AMBIGUOUS, AND EQUIVOCAL

If we consider the scientific enterprise as staffed by fallible humans, for whom arriving at explanations for phenomena may not only be a matter of rational choice, then it becomes important to appreciate to students the esthetic, sociocultural, or other rules with which humans interpret natural phenomena, many of which can be contextual and implicit. It has long been said that nature does not speak for itself, but humans have to interpret it. Considering the issues that we have surveyed above, the utility of scientific knowledge in daily lives, and the numerous socioscientific issues that we are confronted with, we contend that one key concept is that which is often encapsulated in the “tentative, yet durable” nature of science that has been frequently repeated as a nature of science instruction goal. This tentativeness arises due to the manner in which empirical investigations have to encounter a nature that Andrew Pickering suggests is full of “nonhuman agency” (Pickering, 1995). On its face, such a stance seems regressive—after all, a significant advancement of the scientific enlightenment has been to rid nature of capricious spirits that animated the natural world and explained why it behaved as it did. Indeed, an interesting critique (over 30 years ago) of the scientific approach found the metaphor of the scientific method as enunciated by Francis Bacon as abhorrent; he is supposed to have said:

For you have but to hound nature in her wanderings, and you will be able when you like to lead and drive her afterward to the same place again. Neither ought a man to make scruple of entering and penetrating into those holes and corners when the inquisition of truth is his whole object

Controversy arose as to whether this metaphor implied rape of nature, or if the word choice meant something different during the time of Bacon (Soble, 1995). Controversy aside, what is clear is that from the early stages of the scientific revolution, and arguably persisting even today, has been this notion of an unchanging natural world governed by deterministic rules, the role of the scientist being the one to “uncover” once and for all, the *mechanism* of nature's function to predict the behavior of systems. However, Pickering (1995) suggests a different metaphor is required for thinking about our interactions with nature. Instead of a passive nature of which we can make perfect representations, we should consider nature as a more active partner into which we enter into what he termed a “dance of agency.”

It is not as if Pickering seeks to dismiss the possibility of the kind of determinism and predictability that we have been able to communicate through our scientific findings. Rather, as a result of close examinations of the work that scientists actually do, it is possible to appreciate that there is a form of material agency that emerges over timescales distinct from that which we typically assign to human agency. For instance, the Australian eucalyptus tree, over the course of multiple human lifespans and in concert with the human actions of deliberate or indiscriminate starting of a fire, had grown to become the dominant species in Australia (Franklin, 2008). Eucalypts require fire events to break their seed pods and are adapted to reproduce quickly in areas where fire has burnt down the competition. The native Australians had lived a nomadic existence and had a tradition of using fires to clear the underbrush of accumulating biomass, starting “cool” fires so that forests could recover. In contrast, European settlers desired a more permanent existence and allowed the underbrush to collect oily eucalyptus shedding. When fires inevitably happened, they burned out of control and threatened human communities. It took the colonial settlers some time to understand the risk, but even then, the mutual to-and-fro of a dance of agency continued, just in a different manner in relation to the actions humans took. As for inanimate objects, Pickering’s original work with the physics of particle detection (Pickering, 1995) shows how the *metaphor* of material agency operates—it is not as though there are conscious agents acting in response to humans. Rather, the work of scientists is to “capture” the phenomena, often by changing the material configurations of equipment, and the underlying explanatory theories, to produce a stable, reproducible demonstration. Even when phenomena can be captured and put to use in the form of applied technologies, there will be a continual need to protect these configurations from a form of decay that is not in principle foreseeable. Pickering points out that the manner in which material agency will respond is “never decisively known in advance.” The work of scientists is never about discovering the “holes and corners” just lying there to be found, but rather, an iterated problem solving often involving the creation of machines (broadly conceived) that help amplify our senses and discern the occurrence of phenomena. The use of these machines, according to Pickering, can be likened to the tuning of analog circuits to a radio station, with the important caveat that the signal frequency is not knowable in advance.

What Pickering invites us to consider is the nature of scientific knowledge itself: just as our human interactions with nature unfold in a mutual dance of agency, our knowledge similarly grows and changes. Instead of a dualistic detachment of form from the substance, we should instead pay more attention to the ways in which the material reality of substances influences the abstract knowledge that we can obtain about nature (Pickering, 2008). Barad (2003) similarly surmises that we may have granted language too much power to determine reality (when in many instances, the direction of fit should be the other way around). What we may term phenomena are not captured merely as a result of our laboratory investigations aided by apparatuses whose arrangements are guided by our representations and serve as neutral, static probes. Our experimental setups are also material in nature, and not platonic ideals; instead, they are:

dynamic (re)configurings of the world, specific agential practices/intra-actions/performances through which specific exclusionary boundaries are enacted [...] Apparatuses are constituted through particular practices that are perpetually open to rearrangements, rearticulations, and other reworkings. This is part of the creativity and difficulty of doing science: getting the instrumentation to work in a particular way for a particular purpose (which is always open to the possibility of being changed during the experiment as different insights are gained). Furthermore, any particular apparatus is always in the process of intra-acting with other apparatuses, and the enfolding of locally stabilized phenomena [...] into subsequent iterations of particular practices constitutes important shifts in the particular apparatus in question and therefore in the nature of the intra-actions that result in the production of new phenomena, and so on. Boundaries do not sit still. (p. 816)

In educating young persons to understand the work of scientists, these perspectives offer us an invitation to think about the role that material interactions play in the development of “scientific understanding,” and perhaps



even what it means to *understand* the representations of science. It would seem that a traditional approach to practical investigations is largely an effort at the demonstration: pedagogical devices made to persuade students of the correctness of our scientific representations. In doing so, we may inadvertently create the conditions where students graduate with the impression that science is more about an infallible means to obtain capital-T versions of the truth about the natural world, instead of a socially contingent set of practices bounded by material processes whose aim is the refinement of questions. As Firestein (2015) reminds us: these ideas are not foreign to practicing scientists, for whom the undergraduate study is typically a period of transition from focusing on answers to thinking about questions. However, he asks rhetorically, “who besides scientists knows this?” (p. 95).

This article is hence a response to this provocation—what might be a way to bring these ontological and epistemic insights into school science; not necessarily in a way that enhances “engagement” for utilitarian ends, but rather as a means to more accurately depict the ways in which scientific knowledge shifts with time? Significantly, how might we communicate the challenge, and beauty of how it is we can have the knowledge, given the proximity of knowledge boundaries, the human nature of our social practices in adjudicating truth claims, and the complexity of how materials act in relation to our human desires.

5 | A DIFFERENT WAY TO THINK ABOUT EXPERIMENTS—THE INTERNATIONAL YOUNG PHYSICISTS TOURNAMENT

We describe here the International Young Physicists' Tournament (IYPT), an annual international competition that draws participants from middle and high school years. Typically, this would be after some years' initiation into formal physics education, but before they begin university education. The IYPT has a 34-year history, beginning in 1988 in the former Soviet Union (even though earlier prototype versions occurred before this). The IYPT was first held outside of Europe in 2004, in Australia; and a recent contest in 2022, attracted 130 student participants from 25 countries. Typically, consortia of universities and national education departments are responsible for organizing within-country tournaments to select representatives. The IYPT poses a unique challenge as compared to other competitions: instead of individuals competing against one another on mostly theoretical questions that they have no foreknowledge of, in the IYPT, problems are announced at the end of each year's tournament for the next year. Participants form five-member teams who have the year to solve a set of 17 empirical problems that either require some theoretical characterization and/or the construction of ingenious physical instrumentation to do so. While the social nature of the tournament poses novel insights for education, the focus of this paper will be on the problem set itself. As to be expected for a tournament at the international level, these problems are not trivial, not in the sense that they involve esoteric phenomena, but that they are amenable to sophisticated analyses typically demonstrated at the level of undergraduate or later work. At tournaments, three teams are grouped in every round, with one party presenting their findings (reporter), another tasked with being critical about the reporters' work (opponent), and the third (reviewer) tasked with critiquing and evaluating the presentations and discussions of the first two. These performances are judged by a panel of physics educators and university scientists (jury), who give subjective scores on the performance of all three teams. We contend that the IYPT model represents a possible prototype for school science if one is no longer satisfied with the industrial-rational model of communicating the rhetoric of conclusions, or even the present challenge of the contradictions posed by teachers used to being epistemic authorities in the classroom (thus avoiding the excesses of relativism) but who nonetheless wish to present the socially constructed (and contested) nature of truth claims. The structure of school instruction in many settings seems designed to bring students towards predetermined “learning objectives,” with which standardized tests are able to determine one's standing in ostensibly meritocratic systems of comparison, despite significant moral objections (Luke, 2011; Sandel, 2020). From this perspective, science (along with science, technology, engineering, and mathematics—STEM) can be preferred as an apparently objective, value-free form of knowledge; especially since its practitioners, its educators, and popularizers have placed strict firewalls on what constitutes

science/STEM knowledge (see, e.g., Hodson, 2003; Lekka-Kowalik, 2010; Rolston, 1988; Slaton, 2015). We acknowledge that schools exist to serve a broad set of purposes, only one of which is *education*, and hence there can be much resistance to changing the way science is taught. Nonetheless, if we wish to present a more accurate picture of how scientific truth claims are made, the IYPT model is one way to proceed. As can be seen later, this model requires significant shifts in the way we understand the practices of science instruction and a suspension of taken-for-granted beliefs about what schools are supposed to be for.

We found the IYPT problem set (archive available at <https://archive.iypt.org/problems/>) and its accompanying instructional model to afford three features which attend to the issues we set out in the opening of this paper. These are: (i) the openness of theoretical choice in analysing phenomena; (ii) the qualitative and subjective nature of the explanatory utility of theories; and (iii) the material contingency of empirical investigations. In what follows, we will be illustrating these concepts through a selection of problems from past IYPT problem sets. We designate these questions as (YYYY/PN) to refer to the Problem number N from the year YYYY. These problems are chosen for their ability to express these conceptual categories and for their ability to engage with a wider audience. The categories were determined based on our experience with the IYPT: as a researcher and jury member in the local YPT competition (Author 1), and as a juror in both the local and international YPT, chair of the local organizing committee, international organizing committee member, and local expert panelist for a country team which has won multiple tournaments (Author 2).

5.1 | The openness of theoretical choice

In contrast to typical school and undergraduate laboratory investigation where the appropriate choice of theory is already prescribed, IYPT problems tend to present phenomena in holistic form, posed in the form of a puzzling scenario for which several possible physical mechanisms and theories could be recruited for its explanation. Most striking are the engineering problems, which are typically the first of the 17 problems in the set. For instance, in the last 3 years, the “Invent Yourself” problem asked:

Build a simple motor whose propulsion is based on corona discharge. Investigate how the rotor's motion depends on relevant parameters and optimize your design for maximum speed at a fixed input voltage. (2019/P1)

Design an instrument for measuring current using its heating effect. What are the accuracy, precision, and limits of the method? (2020/P1)

Design a boat that moves only due to the periodical mechanical movements of its internal parts and which only interacts with the environment (air, water) through its stiff hull. Optimize the parameters of your boat for maximum speed. (2021/P1)

Participants are expected to build the device, not only theorize its design. This problem typically presents two or more competing physical effects that the participants have to resolve to optimize the design for the desired effect. Such a task is fairly common among physics practitioners who often have to create devices that are impossible to find “off the shelf.” In addition, this problem will prompt participants to quantitatively characterize the performance of their invention, again a task that is typically expected in experimental physics.

For the 2020 problem, two effects compete to affect the performance of the invention. On the one hand, attempts to “read” a current will work better if more electrical energy is transformed into heat (e.g., in a resistor) or other forms of energy. However, doing so will influence the current in the circuit being tested—contradicting the desire for the ideal ammeter to have zero resistance. In addition to this competing effect, which is a general problem



that affects many forms of measurement (e.g., gas pressure, temperature, liquid flow rate), this invention also needs to manage heat effectively. On the one hand, gathering and retaining as much heat as possible will ensure that the electrical energy lost to heat is minimized. However, if this heat is not lost quickly, the part responding to heat will not achieve thermal equilibrium rapidly enough to make a useful ammeter. Additionally, this problem does not prescribe or otherwise limit participants to particular physical effects. Among participants at the local tournament, we noticed apparatus where: (i) wire heating led to its expansion, and this expansion is magnified via a capstan-mounted pointer; (ii) wire expansion is magnified by a laser bouncing off a mounted mirror; (iii) wire expansion breaks contact with a circuit, the time taken for this to happen being recorded via programmable microcontroller; and (iv) wire heating directly measured with infrared camera. Indeed, the very basis of a measuring instrument is the conversion of one physical effect into another.

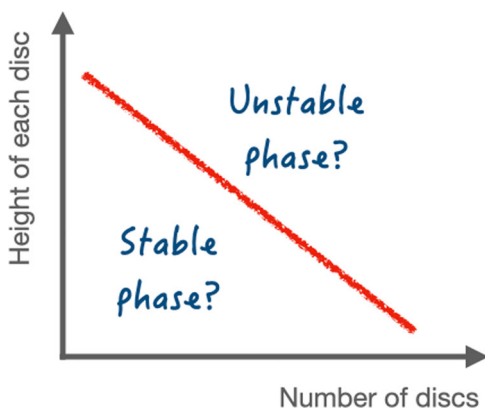
For other problems, their general form is presented as an interesting physical phenomenon, for which the approach is not constrained. For example, the following three problems are typical of the challenge posed by the IYPT:

Identical discs are stacked one on top of another to form a freestanding tower. The bottom disc can be removed by applying a sudden horizontal force such that the rest of the tower will drop down onto the surface and the tower remains standing. Investigate the phenomenon and determine the conditions that allow the tower to remain standing. (2020/P14)

Allow a tuning fork or another simple oscillator to vibrate against a sheet of paper with a weak contact between them. The frequency of the resulting sound can have a lower frequency than the tuning fork's fundamental frequency. Investigate this phenomenon. (2019/P3)

When a drinking straw is placed in a glass of carbonated drink, it can rise up, sometimes toppling over the edge of the glass. Investigate and explain the motion of the straw and determine the conditions under which the straw will topple. (2018/P5)

These questions present a challenge in that they are not analytically solvable in a complete way. Even though the specific physics principles can be well understood for simplified cases, simple physical interactions can limit the applicability of these principles, requiring a great deal of sophistication to generate numerical solutions. These questions highlight the limits of our knowledge and show participants the quality of our ignorance—it is not as if we do not have any knowledge whatsoever about these contexts, but it is that the regions of predictability can be hard to foresee in advance. For instance, an initial approach to the 2020 Falling Towers problem might intuitively suggest that, for a certain height of the disc, the tower should be stable until a threshold, and that this threshold is greater for a shorter disc height. A first guess at constructing a phase diagram might be represented as:



Even if the general form of the sketch may be correct, the exact shape of the graph demarcating the phases is not known at the outset—no well-known physical principles exist that describe this relationship. This form of problem, of exploring the “phase space” of the complex interaction, appears to be a recurring form of the tournament challenge. Although the two-disc problem is well understood, the problem becomes complex for three discs or more. Theories that may be enlisted to understand this problem include the Coulomb–Amonton law of dry friction, but then this theory is only predictive of a known state of motion between the interacting surfaces (static or kinetic friction). In this problem, the choice of theory needs to be iteratively determined by reference to the state of motion at the preceding moment, a method that is essentially intractable to pen-and-paper approaches and which instead requires a computational simulation.

For the 2019 Undertone Sound problem, where the tuning fork strikes the sheet of paper at a fraction of its oscillating frequency, the stability of the phenomena similarly depends on factors (such as distance between oscillator and sheet, oscillating amplitude and frequency, sheet stiffness) that interact in ways to provide regions where the phenomena exist and the other regions where it does not. Lastly, for the 2018 Drinking Straw problem, the straw rising could be explained by either considering the momentum imparted by rising bubbles, or by the buoyant forces of the bubbles that adhere to the straw. While individual physical effects can be fairly well understood, trying to disentangle between the two effects and become precise about the contribution of the different mechanisms is not an easy task. Participants face the challenge of choosing the appropriate theory that would explain different regimes of behavior as different subdisciplines of physics contribute in complex ways, and this appears to be the norm rather than the reductive physics that is presented in textbooks.

To reiterate, all these problems reveal the ways in which our knowledge is limited and our ignorance more significant. Even in simple interactions that can be achieved within typical school laboratories, the precision of our predictions that we typically take for granted has already broken down.

5.2 | The qualitative and subjective nature of the explanatory utility of theories

As these problems are not analytically closed-ended, practicing scientists usually use some form of modeling to simplify, understand, and predict the behavior of a physical system. The simplest way we teach this to students is in the form of establishing a calibration curve—bring the system through repeated trials, adjust variables, and then record outcomes. It is then possible to suggest a mathematical relationship that would best fit the known data, and then be able to predict values within the tested region. However, doing so is limiting as there is little (or no) predictive value outside of the tested range. More significantly, utilizing statistical methods (such as regression) provides little by way of physical insight into *why* the system behaves as it does, and which of the competing effects is responsible for the resulting behavior. The distinction here we want to draw is between a correlational, inductive collection of observations and a qualitative appreciation of the causal factors that explain why the system would behave as it did. From our background experience of tournament proceedings, a significant difference between higher and lower-performing teams appears to be in the manner in which the teams are able to use *theory* in its most accurate sense—as a means to *explain* why their experimental setups behave the way they do.

For the Falling Towers problem, in a typical educational presentation of problems involving friction, the state of motion is given explicitly, and therefore no ambiguity exists on the form of friction (kinetic or static) to use. In contrast, the multidisc problem needs to iteratively consider the pre-existing state of motion before deciding on what form of friction to use. Ideally, these questions require participants to appreciate computational methods for what they are: “helper” methods, tools directed by physics to amplify the human abilities to observe and compute, rather than as “black boxed” methods into which unthinking investigators are supposed to collect data for. Here, it is instructive to return to the famous words of George Box, from almost half a century ago, that “all models are wrong” (Box, 1976). Box argued that the value of models derives from an iteration between theory and practice, and asserted that a good scientist “must have the flexibility and courage to seek out, recognize, and exploit such



errors—especially his own. In particular, using Bacon's analogy, he must not be like Pygmalion and fall in love with his model" (p. 791, masculine pronouns in original). Box also warned about the problems that might arise if this iterative feedback loop between theory and practice were to be broken:

The maladies which result may be called *cookbookery* and *mathemistry*. The symptoms of the former are a tendency to force all problems into the molds of one or two routine techniques, insufficient thought being given to the real objectives of the investigation or to the relevance of the assumptions implied by the imposed method [...] Mathemistry is characterized by development of theory for theory's sake, which since it seldom touches down with practice, has a tendency to redefine the problem rather than solve it. Typically, there has once been a statistical problem with scientific relevance but this has long since been lost sight of. (p. 797, emphases in original)

Symptoms of these maladies occur even among some participants of the IYPT. There are mathematical software packages designed to solve the complicated equations that describe dynamic systems, and a hallmark of weaker teams is their usage of these packages to generate almost a "variable soup" of equations loaded with correction factors, accompanied by a general lack of ability to explain to opponent teams and the jury what these factors meant for how the system would behave.

A general strategy for modeling complex physical behavior to understand and make predictions of it has been to make simplifying assumptions about the empirical phenomena to make the mathematics tractable. Take the computation of fluid flow; our current best knowledge is encapsulated in the Navier–Stokes equations, which are essentially insolvable analytically. Consider this recent problem:

When rotating a rod coated with a viscous liquid (e.g. honey), under certain conditions the liquid will stop draining. Investigate this phenomenon. (2022/P16)

Implicit in the problem statement is the use of a rod as a mathematically convenient surrogate for a honey dipper or spoon, suggesting that the cylindrical symmetry of a rod may be exploited as a simplifying assumption. To compute fluid flow, i.e. velocity vector field \vec{u} as a function of the cylindrical coordinates r , ϕ , z , and time t , requires the use of the Navier–Stokes equations, given below for incompressible flow in cylindrical coordinates.

$$\rho \left[\frac{\partial u_r}{\partial t} + u_r \frac{\partial u_r}{\partial r} + \frac{u_\phi}{r} \frac{\partial u_r}{\partial \phi} + u_z \frac{\partial u_r}{\partial z} - \frac{(u_\phi)^2}{r} \right] = - \frac{\partial p}{\partial r} + \rho g_r + \mu \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial u_r}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 u_r}{\partial \phi^2} + \frac{\partial^2 u_r}{\partial z^2} - \frac{u_r}{r^2} - \frac{2}{r^2} \frac{\partial u_\phi}{\partial \phi} \right],$$

$$\rho \left[\frac{\partial u_\phi}{\partial t} + u_r \frac{\partial u_\phi}{\partial r} + \frac{u_\phi}{r} \frac{\partial u_\phi}{\partial \phi} + u_z \frac{\partial u_\phi}{\partial z} + \frac{u_r u_\phi}{r} \right] = - \frac{1}{r} \frac{\partial p}{\partial \phi} + \rho g_\phi + \mu \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial u_\phi}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 u_\phi}{\partial \phi^2} + \frac{\partial^2 u_\phi}{\partial z^2} - \frac{u_\phi}{r^2} + \frac{2}{r^2} \frac{\partial u_r}{\partial \phi} \right],$$

$$\rho \left[\frac{\partial u_z}{\partial t} + u_r \frac{\partial u_z}{\partial r} + \frac{u_\phi}{r} \frac{\partial u_z}{\partial \phi} + u_z \frac{\partial u_z}{\partial z} \right] = - \frac{\partial p}{\partial z} + \rho g_z + \mu \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial u_z}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 u_z}{\partial \phi^2} + \frac{\partial^2 u_z}{\partial z^2} \right].$$

Although looking unwieldy to the uninitiated, these three equations are essentially statements of Newton's second law ($\vec{F} = m\vec{a}$) in three cylindrical coordinates. The terms on the left-hand side correspond to the $m\vec{a}$ term in the second law, here parameterized by the fluid density ρ . The right-hand side corresponds to the forces that the fluid experiences: the first term is the pressure (p) gradient, the second represents external forces such as gravity \vec{g} , and the

set of terms in square brackets represents internal forces parameterized by fluid viscosity μ . In addition, the mass continuity equation $\nabla \cdot \vec{u} = 0$ (for incompressible fluids) is also applicable.

To use these equations to describe and explain the context of the problem requires the use of *judicious approximations*. Geometrical simplifications such as orienting the rod horizontally, and reducing the problem to two-dimensions by assuming no dependence of the velocity field on the axial coordinate z , may be applied. Other approaches to reduce mathematical complications may be to limit the study to steady-state solutions, that is, solutions without time-dependence, to only uniform rotation of the rod, or to *choose to ignore* less dominant forces such as surface tension. Other mathematical techniques can be used to simplify—if we could *assume* (or make it so) that the thickness of the honey layer surrounding the rod (h) is smaller than the radius of the rod (R), a correction term corresponding to the ratio of thickness against the radius can be invented ($\epsilon \equiv h/R < 1$), with an expansion in powers of this ratio ϵ , ϵ^2 , ϵ^3 , ... being used as a means to decide on the precision. In this approximation, lower powers are significant, and higher-order ones are only called upon if more precision is needed. Indeed, in some cases, the advance in understanding is in inventing better mathematical approximations to simplify the general solution (e.g., Evans et al., 2004; Moffatt, 1977), but whether or not these assumptions are “safe” in that they can be applied over more general contexts require empirical verification.

The point of this extensive mathematical detour is to illustrate the kinds of decision-making that participants have to negotiate. Mathematics affords humans with a particular precision not accessible to natural language description, but an unfortunate downside of such precision is that these general equations can quickly become unmanageable and incomprehensible. Not all terms are equally important for calculating the outcome, and approximations can be made to simplify the mathematics. However, the choice of approximation can be subjective, and some approximations produce more reliable outcomes than others. How this choice is to be made can be a form of tacit knowledge, derived from working with empirical contexts and appreciating how the mathematical descriptions relate to the empirical context. If (as Box asserts) all models are wrong, it might follow that some models are more wrong than others. When, at some point, the empirical findings do not agree with the mathematical predictions of the equation, it might be possible to invent some correction factors to “make it work”—but that begs the same problem that we discussed earlier—at which point would physicists/participants decide that their initial choice of simplifying assumptions was incorrect and that another set should be chosen instead? What ‘understanding’ a problem, and how one “explains” a problem to demonstrate one’s understanding, becomes a performative act during IYPT debate sessions, endearingly called “physics fights.” These sessions are adjudicated by a panel of experts, and while the accuracy of physics is a criterion for judging, the ambiguity of many problems means that the kind of accuracy being assessed is not a replication of a normative form, but rather the judiciousness of subjective choices being made to grapple with the physics of the problem.

Another sense in which we noticed the IYPT problems required theoretical agreement with empirical context occurs in the way common, everyday phenomena are actually not sufficiently explained by recourse to typical textbook explanations. It is not as though these explanations are mistaken, but they are simplifications that do not give adequately precise predictions if one actually bothers to make measurements. For the Undertone Sound problem, for example, some typical first-order explanations might approximate the sheet of paper as a cantilever or an elastic membrane; in reality, however, the paper is neither a truly elastic sheet nor a rigid cantilever, being a fibrous sheet with its strands randomly aligned. While these approximations might provide some theoretical support, recourse to experiment should quickly persuade one to the limits of rudimentary textbook models. Once again, the choice of simplifying assumption needs to be tested, and it can be possible that the “correct” explanation can be a superposition of both, or actually neither as properties might become emergent in the combination. This example highlights the proximity of knowledge boundaries and the quality of ignorance that ought to accompany our studies in science. Instead of a position of hubris that claims we can extend our knowledge indefinitely, a more humble acceptance of the limits of our knowledge and how difficult it can be to extend our knowledge into apparently mundane contexts. Whether the practical context provides incontrovertible evidence for one



interpretation or another is not obvious, and it can be a matter of interpretation contested between two teams if the results support one explanation or another.

To summarize, the empirical context of real-world phenomena is often complex and consists of interactions between competing physical effects, or effects sensitive to time and the geometrical arrangement of the system (among other things). The IYPT problems recognize the context-sensitivity of the knowledge of physics, eschewing abstract universal generalizability that is typically communicated through textbooks. Social disputes and collaboration to interpret phenomena also become foregrounded in this approach that acknowledges that nature does not speak by itself and requires our collective interpretation, with received wisdom merely as a starting point and not the final word.

5.3 | The material contingency of empirical investigations

Simply because the IYPT problem sets require participants to work within empirical contexts, the potential for students to confront the material contingency is already apparent. Consider the following three problems:

A heavy particle may fall through a horizontal soap film without rupturing it. However, a light particle may not penetrate the film and may remain on its surface. Investigate the properties of such a membrane filter. (2020/P8)

Two steel balls that are joined together can be spun at incredibly high frequency by first spinning them by hand and then blowing on them through a tube, e.g. a drinking straw. Explain and investigate this phenomenon. (2019/P6)

In the Leidenfrost effect, a water drop placed on a hot surface can survive for minutes. Under certain circumstances, such a drop develops oscillating star shapes. Induce different oscillatory modes and investigate them. (2017/P5)

A key characteristic of the IYPT problems is a form of underspecification of the phenomena to be studied: there is never a “standard apparatus” which teams are prescribed. The Soap Membrane Filter problem (2020/P8), for instance, merely suggests that “heavy” and “light” particles may be screened by a soap film, without even hinting about the approximate mass ranges of this effect, let alone other factors such as object geometry, density, surface finish and so on. A certain degree of “trial-and-error,” or, using the language of Pickering’s concept of the dance of agency, tuning, is required for participants to even observe the phenomenon in practice, let alone attempt to “capture” the phenomena by designing clever apparatus that allows measurable parameters to be read and particular predictions possible.

There is also a tacit aspect of experimentation that is often not documented by practitioners in scientific journal articles. Even though journals of experimental science do publish reports of novel methods, the craftwork of creating experimental setups with a view to isolating phenomena for the theoretical study is often perceived as unimportant or merely a form of engineering at best. However, despite a lack of attention, these skills are crucial in performing investigations. In the Leidenfrost Stars problem (2017/P5), inducing multiple, stable, pointed star shapes was vital in being able to “induce different oscillatory modes” so that quantitative characterization could be made. During the tournament, one team managed to induce a stable nine-pointed star while others only managed four or five. They managed to do so by careful observation and control of the drop height, residual horizontal velocity on impact, and most significantly, finding a heated surface with a slight concavity which caused the drop to have a tendency to return towards the center instead of leaving the edge. This then allowed the oscillations to persist for longer, and better observations. The difficulty of achieving this result cannot be understated—the higher-order

oscillatory modes required a higher degree of energy and were increasingly less likely to occur. Despite these challenges this team managed to produce reproducible, well-documented results that can provide data to help resolve what appears to be an active theoretical dispute among theoretical models (Bouillant et al., 2021). Some participants have actually gone on to publish their findings in physics journals (Chua, 2020; Fu, 2020a, 2020b; Jaikumar & Yang, 2022), demonstrating how our knowledge is incomplete for even some “simple” cases.

Although IYPT problems do not specify the physics principles required to understand the phenomena, some problems have either been completely or partially analyzed and their findings published in scientific journals (see, e.g., Jackson et al., 2015; Stogin et al., 2018). Even though these articles provide a “model answer” of sorts to aid investigations, we contend that because of word limits and the format of publication, these reports never provide sufficient detail (e.g., Ha et al., 2018) as to the manner in which the practical matters are carried out. In any case, explaining these details does not sufficiently capture the tacit details of the *feel* of working with materials, as well as the ways in which unexpected occurrences were managed to arrive at the result. The logic of reporting is also never the same as the logic of discovery; the article does not constitute a chronological sequence of events. Also almost never mentioned is what constitutes a *failure* to obtain a result—such negative or nonfindings can potentially assist investigators in pruning off potential unproductive lines of inquiry, but since they are not published, IYPT participants have to navigate through failures themselves.

To reiterate, we found that, since all the IYPT problems are empirical in nature, confronting material contingency was a default mode of their investigations. Because of the potential for ambiguity and uncertainty in empirical investigations, IYPT problems give participants a first-hand experience of the somewhat flexible relationship of our representations to the phenomena, as well as how closely the boundary of knowledge is to ordinary circumstances that we normally take for granted as being “completely explained” by the knowledge contained in textbooks.

6 | CAN WE THINK OF SCIENCE EDUCATION DIFFERENTLY?

The typical approach to physics instruction is one where topics are taught independently, with little connection to each other or to practical contexts where physical effects commonly interfere with one another. Deeply seated in the principle of reductionism that pervades all of the scientific enterprises, we recognize that it might be ideal for learners to acquire conceptual understanding without the distraction of competing effects. However, such an approach fundamentally misrepresents natural phenomena as they occur, and practical investigations as we design them. Certainly, the goal of scientific experimentation is to disentangle the competing effects, to arrive at some precision as to how much each physical effect contributes to the observable outcomes. However, this act of disentangling is in itself a vital and valuable skill, that most students will not have the experience of until late in their training. It is in this sense that we mean our notion of improving the quality of ignorance. Even for practicing physicists, how physical effects will interact with one another is not necessarily well known, and is highly dependent on contextual factors. The fact that many of these problems are found worthy of publication in research journals underlines a significant reason why we believe the IYPT problems to be distinct—not only are these problems the kind encountered by practicing scientists, but they also show how the boundaries of our knowledge often hide merely at the edges of situations that we take for granted.

One might object that such a problem for education is intolerable as the possible interactions between diverse effects are not in principle limited. Yet, this might actually be the point—since physical interactions occur all the time, even in experimental equipment specifically designed to isolate effects, the appropriate epistemic attitude we should adopt is one in that scientific knowledge is more limited. At one extreme, even in simple dynamics experiments where ideal conditions stipulate the existence of frictionless surfaces and no air resistance, educators should minimally acknowledge the difficulty of attaining these ideal conditions, and that our knowledge can be limited in fairly common “real-life” situations. The horizon of our predictive abilities may actually be a lot more



limited than the ideal cases would have us believe, and this is especially so when multiple effects compete, or when effects do not follow proportional or linear reasoning. The end result might be that systems can behave in counterintuitive ways.

Returning again to issues concerning the public understanding of science, such an approach to practical investigations should be seen as part of a holistic strategy designed to inform students about the ways in which our knowledge is limited, and how despite these limitations, the knowledge we do have is hard-won and is reliable. We propose the IYPT model of practical investigation as a means to also reopen the discussion of what it means to actually understand science—whether it is sufficient for students to demonstrate competence in symbolic manipulation of abstract representations; or, as we propose, that understanding needs to arise from a qualitative, tacit, contextual appreciation of the relationship between phenomena that one is confronted with, and the possibility that a quantitative, explicit, and context-independent representation can actually be obtained. A plausible objection to our proposal for school science might be that school science is not intended to emulate practitioners' science; there are good pedagogical reasons why we should minimize the possibility of confusion, for instance. However, as we consider such rationales it seems to us that these only make sense if we have very narrow and possibly outdated definitions of what it means for one to *understand* something—here, the long shadow of recitation models of learning may be a more insidious influence than we care to acknowledge.

Here, it is appropriate to discuss the distinction made by the philosopher of education Harðarson (2017) between what he termed the open and closed-ended aims of education. Harðarson asks: What might it mean to say that one *understands* gravity (for instance)? Would a sufficient condition be the ability to perform simple calculations using Newton's formula? Or would it be necessary to explain how massive objects distort space-time, how black holes behave, or why scientists spent years searching for the Higgs boson? For Harðarson, the quest to understand something is an example of an open-ended aim, which necessarily cannot have an endpoint. In contrast, in more typical curriculum goals for school (science), we more commonly contend ourselves with close-ended aims that can be easily caused by controllable means, and which also can be easily assessed. However, such a narrow technocratic view is unnecessarily limiting as an excessive focus on outcomes prevents us from seeing the experience of education as rewarding *in and of itself*. We might want on occasion to ask—what good is education *for*? As a response, we also might want to suppose that it can be for its own good; to know, to appreciate the beauty of our abilities to know, and to develop a humility of what we don't yet know or cannot possibly know.

Another plausible objection stems from the competitive nature of the IYPT; the students who participate in this tournament are typically highly motivated, high-performing students, many of whom appear destined for careers in science and technology. Working on the boundaries of knowledge does not seem to be particularly apt for some students (so the conventional wisdom might suggest) whose degree of motivation may not be as high, and for whom gaps in knowledge might be better served by instruction first. On the contrary, we believe that the problem of motivation is resolved when students appreciate why it is certain forms of knowledge are needed in the first place. Instead of discrete pieces of knowledge delivered programmatically by an all-knowing educator, it might be useful to attribute some agency to students for their own learning instead. The educator's role in this, as we have observed for teams preparing for the tournament, shifts towards a facilitator of inquiry, a very experienced senior colleague whose ideas may nonetheless need to shift to match the neutral arbiter of the phenomenon. Again, such an approach will no doubt stand in contradiction to taken-for-granted notions of what constitutes ideal schooling practices, especially in systems where the demands for accountability are high. For these cases, therefore, work needs to be done to shift the status quo.

Hence, we return to the mischievous title of this article, with its apparent paradox. We conventionally consider learning as an antidote to ignorance, as if these were binary states. We also typically have negative perceptions of ignorance, as a mental state to be avoided, and preferably filled with knowledge. However, as much as we can appreciate that not all forms of knowledge confer equal benefits, we should similarly accept that not all forms of ignorance are equal. We advance the notion here that it can be vitally important to know the ways in which we are ignorant, and how, despite appearances to the contrary, it is possible that our knowledge is limited, with ignorance

waiting very close to the margins of the most quotidian of circumstances. A proverb suggests that “a little knowledge is a dangerous thing,” and it seems that the degree of confidence that we traditionally place upon typical approaches to school science instruction may serve too much to set up the circumstances for this form of epistemic danger in the public understanding of science. We hope that with these arguments for deepening the public appreciation of the truth of science (and indirectly, the beauty that we can have knowledge), we can better attend to its public utility.

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