
Whole
Science

Whole Science

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1 | Introduction: The Challenge of Reliable Science and Trust

Science everywhere informs personal and public decision making. Everyone, as both consumer and citizen, relies on science. Yet significant sectors of the public discount the scientific consensus on climate change, vaccine and GMO safety, public health measures, and the future of energy, among other topics. Policy makers may appeal to "alternative" science. Sometimes, individuals are misinformed [1]. Other times, there is insufficient transparency or understanding to exercise trust in scientific research or its institutions [2-4].

Science education thus needs to help students develop an understanding how science works, in order to interpret the reliability of the claims that shape their lives. This fundamental civic aim of science education goes beyond conceptual content — the conventional textbook. It goes beyond skills in "scientific practices" (or scientific reasoning or argumentation or *doing* science). This additional focus has been called, variously, the "nature of science," "ideas about science." "science as a way of knowing," "the strategy and tactics of science," or "theory of knowledge," among other banners, and science educators have recognized its core value for nearly a century [5-13].

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Yet despite its acknowledged importance, this goal remains peripheral to most curriculum standards internationally. As noted by Olson [14], several problems seem to plague the efforts. First, the rhetorical aims of education are only weakly connected to the details of the reflections about science. Second, the concepts seem poorly articulated, disjoint, and not well unified into a coherent vision. Third, teachers are provided very few models to guide classroom instruction. Fourth, teachers are not sufficiently prepared with the requisite background knowledge or teaching methods. This report thus articulates a framework for conceptualizing and enacting this essential dimension of science education.

The core strategy is to engage students in episodes of science, highlighting concretely how scientists develop and communicate reliable knowledge. Rather than endeavor to reduce science to a particular "method" or to prescribe a set of abstract tenets or features of science, the aim is to illustrate how science works — at a human level and in a cultural context. How are its claims justified? The view is holistic and contextual and is thus called a *Whole Science* approach.

The first section to follow explains how "wholeness" may be interpreted in four distinct ways. First, there is no exclusive checklist of basic elements, such as might be used to sharply "demarcate" science from non-science. Narratives and concrete cases of science help illustrate the broad diversity of factors that shape how scientists develop trustworthy claims. Whole Science. Second, the primary concern is understanding the reliability of scientific claims both in the expert research community and as they appear in public media. The framework spans the multiple steps of the process — from test tubes to YouTube. Or: from lab book to Facebook. Whole Science. Third, the approach draws on richly contextualized narratives of authentic science, rather than decontextualized activities, short anecdotes, or abstract generalizations. Whole Science. Finally, Whole Science is whole in the sense of rendering public science as ideally by everyone, for everyone.

A Whole Science approach notably focuses on epistemics: “knowing why.” This complements other familiar science education goals: knowing about the world through scientific concepts or explanations (“knowing that”), and developing scientific reasoning skills, perhaps to use as a career scientist (“knowing how”) [12, 15-16]. The central theme is reliability, the foundation of trust. We need to make science meaningful beyond the walls of a lab or the fences of a field site. The local cultural context and students’ lives thus function as benchmarks for determining what “ideas about science” count as relevant to science education, not a set of idealized, generalized or abstract curricular standards.

A Whole Science approach to nature-of-science education was introduced 15 years ago [17]. Since then, the promise of a Whole Science perspective has been elaborated more fully and systematically [18-21], proving widely informative. Yet these clarifications have been presented in many separate publications, making it difficult to appreciate the wide scope and unified nature of this perspective. Accordingly, this publication offers a consolidated overview. It serves as a single comprehensive and programmatic presentation of Whole Science. Readers are invited to refer to the earlier publications for additional details.

For example, Whole Science serves as a framework for introducing relevant insights from the history, philosophy and sociology of science (and allied fields) [22] and for designing historically informed inquiry lessons [19, 23-25]. In addition, it helps articulate the role of argumentation in science education [26] and highlights how scientific errors of various types can help students understanding how science works [27]. It has opened productive links between science and social justice concerns [28] and between misinformation and science media literacy [29-32]. This report extends the earlier analyses by showing how Whole Science helps address and remedy the problems (noted above) in integrating the general topic of the nature of science (or ideas about science) into mainstream science education.

the Whole Science view is described in detail in Section 2, and its relationhsip to other familiar approaches in science education explored in Section 3. Section 4 addresses the acknowledged problem of how to teach ideas-about-science (or nature of science), especially in a style consistent with educational theory. The Whole Science approach includes a toolkit for contextualizing science, making it meaningful to students, and empowering them to use scientific knowledge to inform their lives. This section also describes how to support teacher education and professional development by providing a framework for ongoing learning about the process and context of science. A concluding section reviews how a Whole Science approach addresses the current problems and surveys some of the available resources already available.

> The Whole Science approach includes a toolkit for contextualizing science, making it meaningful to students, and empowering them to use scientific knowledge to inform their lives.

2 | The Basics of a Whole Science Approach

The treatment of ideas *about* science should begin with how the topic fits within a full science curriculum. Programmatic statements about the nature of science, for example, can be found in major curricular documents, yet they are generally not well articulated at the level of content or methods [18]. Historically, most visions of (and justifications for) public science education have included a major role for preparing citizens and consumers to engage with scientific claims that can inform public policy and personal choices [10, 12, 15-16]. That is, we should help develop informed, rather than blind, trust in those claims [32]. Ideally, then, a primary focus must be enabling students to interpret whether (or when) any particular claim in the media is appropriately justified.

2.1. Open Inventory

Conventionally, educators have endeavored to distill a core set of principles that can fulfill this function: What is the general nature of scientific knowledge and how is it related to its methods of inquiry? [11, 33-34]. That effort has largely endeavored to reduce an outsider’s view of science to a few salient tenets. The starting point for Whole Science thinking is based on challenging the reductionistic and abstracting impulse [35-37]. Steeped in the diverse views of Science Studies (encompassing history, philosophy, and sociology of science, along with other allied fields), it acknowledges that science is complex and multi-faceted [20, 22, 38-39].

Many factors shape the reliability of scientific claims. ...The consumer of science needs to be prepared to encounter any of them — although not necessarily to master them all.

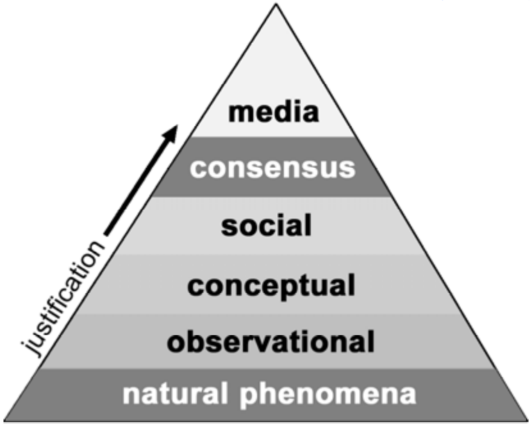
Many factors shape the reliability of scientific claims [40-41]. For example, empirical evidence matters. But so, too, does possible gender, race, or class bias. Investigations can be confounded by hidden variables, hence a need for controlled experiments. Claims may be biased by conflicts of interest, hence a need for evidence-based critical discourse. Logical arguments may be sought, but cognitive biases can lead us astray and instead foster empty rationalizations. Fraud or questionable research practices may intrude. Instruments may malfunction and yield ghostly artifacts. Samples may become contaminated. Statistical analysis may be needed to decipher patterns in apparently chaotic data. Evidence may be susceptible to multiple conflicting interpretations, prompting further studies. Research programs may be mired in communal confirmation bias, while insights from “outsiders” may come to the rescue. All these factors—and more (not to be limited by a checklist)—are potentially significant in different cases. They will be familiar to those who have ventured beyond the artificial world of “School Science,” engaged in research themselves, or followed science documentaries, podcasts, or journalistic accounts. Quite an array of NOS factors: a reminder of the holistic posture of Whole Science

That is, understanding how just a few factors influence science will not suffice. The consumer of science needs to be prepared to encounter any of them — although not necessarily to master them all. A Whole Science approach thus rejects short, standardized checklists of presumably “basic” principles. Tidy lists are beguiling. They are simple and easy. Yet they can easily oversimplify matters, giving a false impression of a set of principles sufficient for interpreting science effectively [35, 37]. Real cases of science in society do not necessarily follow the simple “rules” imposed on them by educators [38, 39]. They do not limit themselves to those prescribed factors. So over many years, teachers need to help students prepare for encountering a wide spectrum of epistemic factors (Appendix, right column). An *open inventory*. Again: Whole Science.

2.2. Justification, from Test Tubes to YouTube

At the same time, teachers benefit from structure. And perhaps a sense of security about what is expected? A reference for being responsibly complete? Figure 1 presents a first-level outline as guidance. The focus is on how we construe the justification for scientific claims, building from raw evidence to the consensus. We can sort these into three layers: observational, conceptual, and social-level [27, 40]. Observational factors include the familiar domain of the lab: measurements, sample size, experimental design, observer bias, controls, instruments, materials and methods—everything that goes into data collection (and doing so reliably). Conceptual factors include logic and argument, of course, but many other cognitive processes: pattern-recognition, statistical analysis, graphing, imagination, concept formation, analogies, model building, theory revision, as well as various forms of subconscious cognitive biases (availability bias, motivated reasoning, and so on). Social-level factors concern the discourse among scientists in a community as they vet and build on each other's claims. These include: publication practices, peer review, credibility judgments, fraud, conflicts of interest, competition and collaboration, and others. This dimension has often been overlooked in traditional science teaching, typically focused on the individual student as a surrogate scientist. It is important to recognize this essential stage of vetting claims from different perspectives and fields of expertise. Reliable science depends critically on this system of checks and balances [32]. So: students need a broad appreciation of the process of justification, distributed across multiple levels.

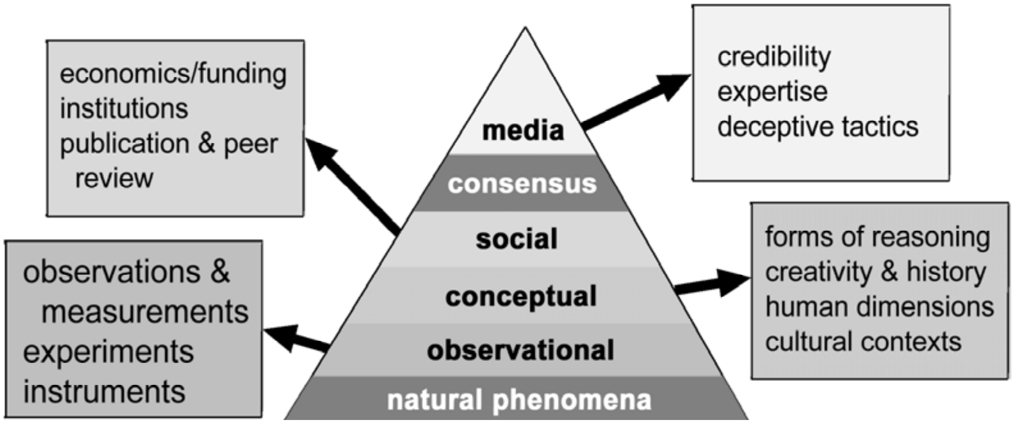
Figure 1. A Whole Science view of epistemic levels, or layers of justification.



To these we may also add an additional, fourth level: communicating science in the public sphere. That is, scientific knowledge is developed within an expert community, governed by the epistemic principles of mutual criticism and accountability. But transferring that knowledge to others is also fraught with questions of reliability: yet another layer of epistemics. Questions of reliability and justification here include credentials, conflicts of interest and appeals to social emotions. This is where misinformation can intrude, for example: Who speaks for science? [29]. The citizen or consumer has much to learn about science media literacy, as part of the nature of science-in-society. This is another aspect of Whole Science: conceptualizing science communication (and public media) as part of a system whereby scientific knowledge is both generated *and conveyed to its ultimate users*. That may not be the responsibility of research scientists themselves, but it is an important part of the science ecosystem. We need to preserve the integrity of scientific knowledge in practical social contexts. A meaningful perspective of the nature of science thus traces knowledge through its whole arc, "from the lab bench to the judicial bench," "from lab book to Facebook," or "from test tubes to YouTube." This construes a view of science-as-research-alone as partial, and situates it in a more holistic view of scientific knowledge, stretching from its roots to the cultural contexts where it bears fruit [42]. A second meaning to Whole Science.

A meaningful perspective of the nature of science traces knowledge through its whole arc, "from test tubes to YouTube".

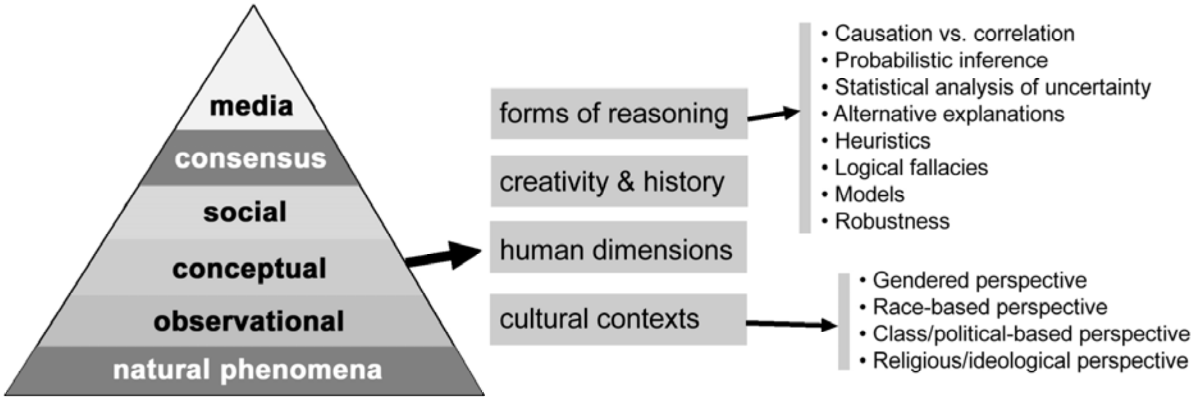
Figure 2. Epistemic dimensions at each level of justification.



The 4-layer scaffolding functions to remind teachers to mindfully address all the levels of scientific work, each important. We may further articulate the distribution of concepts on a finer scale — here, partitioned into 13 categories (Figure 2; see also Appendix, center column) [17, 20]. The categories are not absolute (nor strictly exhaustive). Rather, they help guide planning an ensemble of lessons over the long term, where the aim is to be both comprehensive and balanced. Not every factor will seem significant in every case — many will recede in an unproblematic background. But as reference points, they keep teachers alert to the diversity of what makes Whole Science "whole." The successive layers of justification, and their sub-categories, provide a bird's-eye structure that provides coherence — another key element found missing in curricular documents on nature of science [18].

The various epistemic dimensions help detail the forms of justification at each epistemic level. For example, observational elements may be resolved into observations and measurements, instruments, and experiments (as major categories). Conceptual elements include forms of reasoning, creativity and history, the human dimension (psychology), and cultural contexts (often biases). Here, for example, we may find a value for feminist, Marxist and indigenous perspectives. Social-level processes include funding, institutions, and publication and peer review. Media literacy includes credibility, expertise, and deceptive tactics. Each of these is addressed widely in Science Studies scholarship [43-44]. Think of them as "distributional guidelines" (intended as ways to self-check for breadth in epistemic lessons)? They are lenses for analysis, guides for inquiry, a framework for questions focused on "why should we trust this claim?"

Figure 3. Epistemic dimensions are further resolved into individual concepts.



Each dimension may be further resolved into the fundamental epistemic concepts (Figure 3). For example, at the general level of observations, experiments may encounter confounders — coincident factors that may mislead the interpretation of results. Hence, researchers are accustomed to using experimental controls for comparison and ensure reliability. Sample size, randomized sampling or replicates may equally be important in different cases. At the conceptual level, cultural contexts may be further resolved into gendered, race-based, class-based or religious perspectives, for example — which may "bias" thinking, sometimes productively, sometimes not. A partial inventory of these concepts — perhaps the ultimate "content" of learning about Whole Science, or epistemics — are catalogued in the Appendix (right column).

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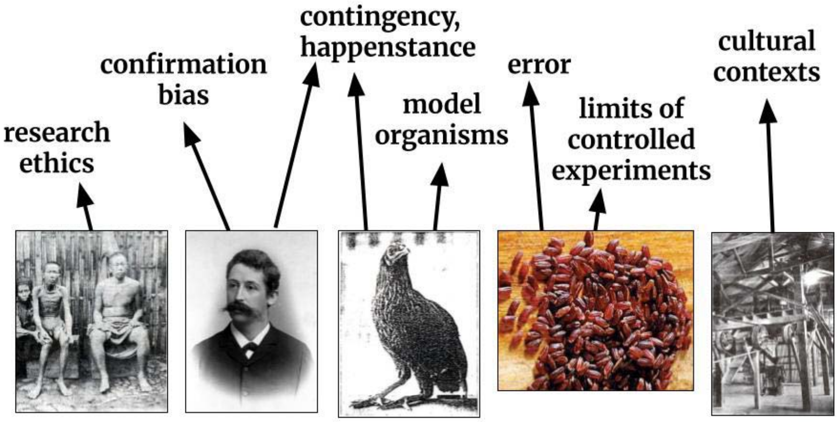
2.3. Integrated, Contextualized Episodes

While a catalog of items can be a handy reference, they must not be mistaken as the ultimate educational targets. For functional scientific literacy—the citizen interpreting scientific claims in public discourse—they need human context. Understanding epistemic justification is not about some remote philosophical appraisal of science as a static "thing" with distinctive properties (or its inherent "nature"). Science is active. Students should see it as a verb. The focus here is about how science works. Teachers thus need to resist the temptation to treat the concepts as discrete items to merely define separately. Science is a process. All these factors interact. And that matters, too. The integration of these elements into a functional whole is also fundamental to what motivates a view of Whole Science. The goal is not to take science apart into isolated components which function independently. The ultimate aim is to understand science as an organic whole, with many contributing elements interconnected as an ensemble. That is, students should learn about the nature of science through episodes of science, or narratives of science-in-the-making. All the components function together in an integrated whole: a third meaning of Whole Science.

The substantive content of NOS is thus not expressed in a limited, privileged list of abstract concepts.
... Whole Science highlights analogical and case-based reasoning, especially valuable where knowledge is complex. It is an important alternative way to organize and index knowledge.

The substantive content of NOS is thus not expressed in a limited, privileged list of abstract concepts. Rather, it builds on *the analysis of diverse, concrete examples of scientific practice*. Fully integrated and contextualized episodes of science are the key vehicle for instruction — addressing Olson's third challenge [18]. Case studies of "Whole Science," exhibiting fully contextualized science-in-action, are essential. The relevant NOS factors are then distilled from them (Figure 4). This flips how learning is normally organized: concept first, then an illustrative example. Here, the concrete case is primary. Later we can ask, "How other cases might be similar?" This process of learning depends on "lateral thinking" — using case studies, exemplars, models, clinical narratives, legal precedents and such. (For a fuller philosophical and historical analysis, see [45]. For an educational overview, see [46].) Whole Science highlights analogical and case-based reasoning, especially valuable where knowledge is complex. It is an important alternative way to organize and index knowledge.

Figure 4. Epistemic concepts distilled in a case about beriberi in the 1890s.



The case studies are where the ideas about science ultimately emerge, in context. Not from some predetermined list, but distilled from analyzing contemporary socioscientific issues and historical cases [47]. The items presented here (Appendix, right column) are merely a (partial) inventory compiled from dozens and dozens of cases. Each teacher — each student — will, over time, assemble and internalize their own catalog of epistemic concepts. They appear in an (open-ended) inventory format here, but in a classroom they will each appear fully contextualized in Whole Science episodes. They are not intended as a definitive checklist, of the sort to be memorized or recited item-for-item on a test. They are not identified here to prompt an exercise in explicit definitions. Rather, each aspect should be linked to some original case(s). The student should, ideally, be able to explain how each contributes to interpreting the reliability of the science, as a consumer or citizen might encounter it in everyday life. They are a basis for future questions about science in society (sample prospective assessments in [17]).

2.4. Science by Everyone, For Everyone

To these concepts, we may add a fourth sense of "wholeness" in science. Namely, "who?" Science is done by everybody and (hopefully) for everybody [35, 48]. For example, "scientists" — those responsible for *doing* science — include the lab technicians, instrument makers, translators and correspondents, often invisible or in the shadows [49-51]. It includes indigenous (or "non-Western") groups, even if they don't have "shiny labs" [52]. And, of course, it includes people across genders and diverse nationalities and ethnicities [53]. The elite may patronize science hoping to justify and reinforce their privilege [54-55]. Corporate interests may pursue science for profit [56-57]. But where resources can be mustered, science also serves the public interest, including the pursuit of social justice [58]. Whole Science is thus a reminder to consider the breadth of contributors to and beneficiaries of science. Accordingly, science education should not be designed just for training future career scientists. It is about understanding the role of science in culture (see also Section 3.2). Whole Science, yet again.

Whole Science is thus a reminder to consider the breadth of contributors to and beneficiaries of science.

2.5. Wholeness

All this discussion may seem to highlight an issue conspicuously unaddressed here: "But what do you mean by '*science*'? How can you have a nature of science or ideas about science without having first clearly defined what science *is*?" Whole Science relegates this habitual first question to a rather peripheral position. Namely, science seems to operate effectively in society without such academic fussing. So, rather than become trapped within the philosophers' age-old (and mostly abandoned) demarcation project, we may adopt a holistic view of science in a cultural setting. Here, science has a widely respected role as a form of expert knowledge, set alongside communication arts, literature, political science, mathematics, fine arts, and so on. Science specializes in knowledge of the natural world (including its causal patterns), hence its intimate association with labs and field work. Most notably, perhaps, science is valued socially because of its *reliability* and *trustworthiness*, based on its distinctive empirically based methods, which afford it great credibility. Hence, Whole Science focuses foremost on these aspects, as the prominent dimensions of science culturally.

That is, if there is a knowledge claim in public discourse, we generally want to know if it is justified, not whether it has earned the label "scientific" (sadly these two terms are too often conflated). Knowing that some claim is "scientific" in character or origin does not tell us whether it is *reliable* or *trustworthy*. That is what ultimately matters. Appeals to the authority of "Science" are thus chiefly political in nature. Hence, in social discourse, sociological boundary disputes [59] largely displace the philosophers' academic concern over demarcation (a project that was largely abandoned decades ago) [60-61]. Of course, the need to defend the legitimacy of science sometimes arises in public debates, but the dynamics of such disputes will inevitably reduce to questions of justification or methods. The political tussles are easily accommodated within the fourth level of epistemics: the public domain of transferring scientific knowledge. (Namely, the issue of public authority is just one aspect of the nature of science, not the nature of science itself.)

One may note additionally that (public) education is primarily concerned with *public* science—the claims that are intended to inform public policy, as well as personal choices about products or lifestyle. Public science requires public justification. For example, the sources must be transparent and accountable—with the provenance of each partial claim traceable to a peer-vetted study. This is normally what we think of when we think of research funded by the (U.S.) National Science Foundation, the (U.S.) National Institutes of Health, universities, government agencies, or philanthropic organizations: knowledge pursued in the public interest. Private science, by contrast, is done by industries, for their own interests [56, 62]. It is often proprietary and not subject to peer review by the community, and thus earns a different status. For example, any public claim by industry research is beset with potential conflict of interest, and would not be considered trustworthy without further vetting [57, 63]. Whole Science at least takes note of the profound differences in commercial vs. public-oriented science (even if they share many methods).

To summarize, the "Whole Science" conceptualization embodies four senses in which the treatment of ideas about science should adopt a holistic and inclusive perspective:

1. whole, in the sense of a full spectrum of epistemic factors, rather than an exclusive checklist;
2. whole, in the sense of addressing the reliability of scientific claims both in the expert research community and in public discourse;
3. whole, in the sense of using richly contextualized and integrated episodes of authentic science ("cross-sections"), rather than decontextualized activities, short anecdotes, or abstract generalizations; and
4. whole, in the sense of science by everyone, for everyone.

The simple label is intended as an economical way to refer simultaneously to all four essential dimensions. Whole Science is thus not a comprehensive "system" or prepackaged curriculum. It is a way of interpreting the challenge of education about the "whys" behind the reliability of scientific claims. It emphasizes the need for understanding science "as a whole" in a way that promotes the civic purpose of science education. It is "a" Whole Science approach, not "the" Whole Science approach.

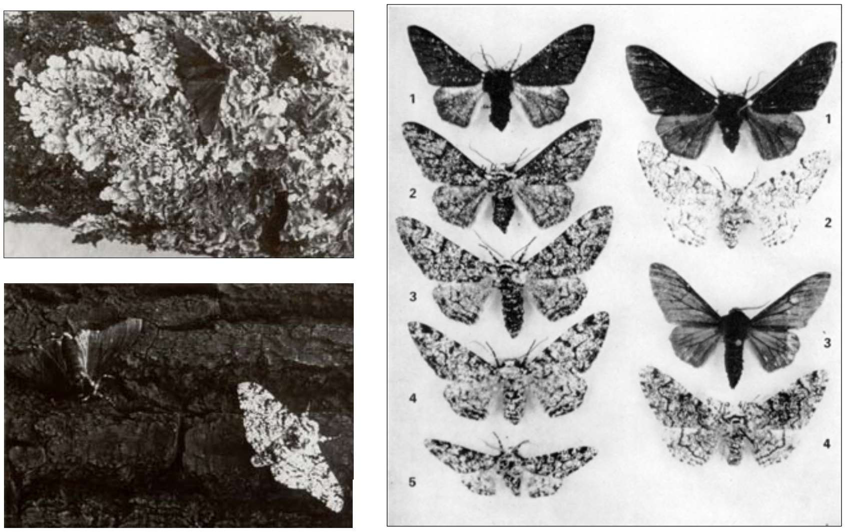
It is "a" Whole Science approach, not "the" Whole Science approach.

The term "Whole Science" was adopted mindfully, to invite an easy analogy to whole foods. That is, just as we should not rely on a diet of highly "refined" or processed foods, so we should not rely on a version of science based on a limited list of abstracted principles, reconstituted into some idealized account of how science *should* work [64-66]. You should not need an advanced degree in philosophy or sociology of science to make sense of it. The goal is to reflect on the whole of science — just as consumers and citizens encounter it in society [42].

The goal is to reflect the whole of science — just as consumers and citizens encounter it in society.

In this sense, Whole Science may be contrasted with the artificial construct sometimes known as "School Science." Whole Science fosters authentic science, resisting the tendency to oversimplify. For example, Kettlewell's famous peppered moths, of natural selection fame, are often portrayed in "black and white" extremes, when the moths exhibit many intermediate forms of grey [20] (Figure 5). Simple laws — Mendel's laws, Boyle's law, Ohm's law — hide the complexities of interpreting nature and mislead students about how science works. Uncertainties — science still in-the-making — and errors are part of the nature of science [41, 67].

Figure 5. The “black-and-white” portrayal of peppered moths, as found in simplified “School Science” (left), versus the hidden complexity of grays in Kettlewell’s original research (right).



Still, Whole Science is not intended as a wholesale reform of science education. That is, the goal is not to displace the “whole” science curriculum. It is an approach specifically for addressing how science works. As the name implies, the perspective should help educators at all levels appreciate that understanding the nature of science is just as much a part of science as scientific concepts, scientific reasoning or experimental skills. A Whole Science approach should help convey that ideas about science are just as essential as scientific ideas.

3 | Whole Science Compared

Whole Science can be more fully understood by comparing it with other approaches to science education and conceptions of the nature of science. It resonates with some, while contrasting sharply with others. It certainly echoes Hodson and Wong’s call for “understanding scientific practice” [37], and Ford’s view of a “grasp of practice” [36], although it delves a bit more deeply into the details.

3.1. The NOS “Consensus List”

In the late 1990s, concerns about teaching the “nature of science” as central to science education were explicit and widely shared. Both Project 2061 [68] and the National Science Education Standards [69] advocated for the importance of teaching the “history and nature of science.” Most educators agreed, however, that the general statements were unacceptably vague and incomplete. McComas and Olson [34] prudently surveyed many international science curriculum documents and extracted a set of ideas commonly found among them. The "agreement" seemed to afford their tally some authority or universality. It was simple and definite — qualities construed as virtues given the circumstances. This has since become known as the "NOS consensus list." Today however, the consensus list ironically no longer enjoys a consensus among educators [18, 70]. For example, Hodson and Wong [37] characterized that widely adopted view as "a disarmingly simple specification of NOS items." Similarly, Bazzul [35] noted the need to "open NOS teaching and learning to a diversity of contexts, knowledges, and practices" that will "allow educators to capture the social, historical, cultural, and political contexts of science." Still, the so-called consensus list continues to be embraced by a handful of educators [71], and it serves as a valuable point of comparison.

Unfortunately, perhaps, the consensus list lacked coherence (reflecting Olson's critique [18]). There was no commonly accepted rationale for NOS education. The "consensus" was thus not the result of a systematic conceptualization effort or collective deliberation. It was merely what most educators at the time seemed to agree was important. In retrospect, one can see that the list was a haphazard assemblage of miscellaneous, sometimes self-contradictory impressions — images shaped by the vestiges of the Kuhnian revolution in philosophy of science and the subsequent "Science Wars," and so embodying a desire to loosen the grip of logical positivism while defending science against the specter of cultural relativism [20].

Any conception of the nature of science should function to help students interpret the reliability of scientific claims encountered in their everyday lives.

A Whole Science approach seeks to remedy this critical deficit by first characterizing the core purposes of teaching about nature of science (or its equivalents). It takes its cue from the aims of science education, as expressed consistently over time and national context [10, 12, 15-16]. As noted earlier, any conception of the nature of science should function to help students interpret the reliability of scientific claims encountered in their everyday lives. We should understand the development of and justification for the knowledge that aims to inform our actions, individually and collectively. NOS understanding of this type may or may not make better scientists (for those few students who choose to pursue scientific careers). That is not the point. Everyone needs to appreciate the basis for and be able to assess expert claims, even when they have no expertise. (And that applies equally to both non-scientists and scientists outside their own specialized field of study.) Whole Science thus gives purpose and coherent focus to any NOS-type curriculum.

Several years after the McComas and Olson analysis, Jonathan Osborne pursued a different strategy for identifying a consensus about NOS with more scholarly grounding. He gathered a set of relevant experts and engaged them in a Delphi study on what "ideas about science" were essential: methods, knowledge, and social institutions [11]. The result resonated strongly with the earlier list, adding a sense of validity. But the Delphi method allows us to interpret more clearly the nature of the Osborne group "consensus." Here, too, agreement was the relevant benchmark for inclusion (at the 66% level). That is, the list identified only the *overlap* of the various perspectives. As a result, many ideas that some participants considered essential were set aside, merely because the opportunity for negotiated discussion had ended. The status of many ideas was left unresolved. In a Whole Science perspective, NOS understanding should adopt as relevant *all* the aspects that the different experts proposed. It should be the inclusive set, not just the shared intersection, of the experts' views. Thus, if there was a justified case for an aspect being relevant, then it should be acknowledged. The task should be organizing, integrating and reconciling views, not seeking uniform agreement.

At the same time, the aspects should not be arbitrary or capricious. Whole Science deliberately tethers "relevance" to public deliberations on the science in socioscientific issues (SSIs; see next section). NOS education should always be responsible to the larger-scale purposes of science education itself. Not "nature of science" for its own sake, or as envisioned in an abstract philosophical sense. But functional nature of science.

The spectrum of epistemic aspects in a Whole Science view is thus not limited to some narrow, prescribed checklist. One might easily imagine that adopting such an extensive repertoire of features might prove unwieldy. For example, it would be nigh impossible for any one teacher to cover it all. But Whole Science encourages approaching reliability in science by posing probing questions. It can thus accommodate diverse and new, possibly unfamiliar cases. Each teacher is thus mainly responsible for introducing a representative sample of inquiries (Figures 1 and 2; columns 1 and 2 in the Appendix). An entire inventory (Appendix, column 3) is just a point of reference. As enacted in the classroom, it remains open and flexible, subject to the individual teacher's discretion. Each teacher will decide based on local context, timely SSIs, the students' background, and the teacher's own background knowledge, allowing the curriculum to be more adaptive — a partial answer to Olson's fourth challenge (Section 1; see also Section 4).

The spectrum of epistemic aspects in a Whole Science view is thus not limited to some narrow, prescribed checklist.

NOS learning may thus vary from one classroom to another. This contrasts dramatically with the custom of a single, universally shared curriculum. Yet the open-endedness yields distinct advantages. Most notably, at the social level of education—across an entire state or nation—it provides for an expanded knowledge base being transmitted to the next generation, where greater knowledge is possible by being distributed across the population. Education is no longer limited to some narrow bare-bones NOS "consensus list." Selection by teachers from a broad "menu" encourages aligning the curriculum with the classroom context, perhaps in response to locally relevant SSIs (for example, dealing with energy needs of a proposed data center; emissions from a local waste incinerator; avian flu threatening parents' egg farms; and so on).

Selection by teachers from a broad "menu" encourages aligning the curriculum with the classroom context, perhaps in response to locally relevant SSIs.

This vision of education diverges from the implicit norm (or ideology) of a uniform, homogeneous education for all. It sees cultural strength in diverse knowledge distributed across the population, rather than a narrower body of knowledge shared by everyone. Politically, decentralizing control of education makes it less likely that schools can be used as vehicles of propaganda [72]. Still, the shared overall structure (Figure 1) ensures that there is common ground for discourse.

A variegated curriculum poses new challenges for assessment, of course. Mass standardized tests, based on a fundamental assumption that all students should be measured for the same knowledge, can no longer apply. But if the history of assessing the consensus list is any indication, this is a good thing. Once the "consensus list" had become established historically, it soon became the basis for the now widely criticized VNOS instrument [73]. Advocates of VNOS often tout having demonstrated its validity. However, this claim may be questioned. First, the construct is artificially simple. There is no evidence that satisfactory performance on the VNOS questionnaire correlates with the ability to effectively analyze real-life SSIs (where NOS understanding is actually applied). Second, the target responses are equally simplistic. Consider a recent study of professional scientists at different stages in their careers. The study — by educators — concluded that nearly half (N=40) had a "naive" view about the "tentativeness" of science [74]. Many of the senior researchers scored "poorly" on the difference between observation and inference, and on the subjectivity of science. These results should have been a red flag. Sample responses indicate that the scientists exhibited appropriate expertise and nuance, not accommodated by the rubric based on stark either-or terms. For example, they were not ready to abandon or discount theories which had decades of evidence, and for which no imaginable alternative was available. Still, the educational researchers felt empowered by their oversimplifications and disparaged the professionals for inadequate responses. Adhering to the arbitrary rubric had become more important than actual understanding. And that is the embarrassing danger of an approach based on simplified checklists: imagining that your derivative, abstracted formulation can trump real expertise. Whole Science, by contrast, emphasizes context and authenticity and a form of assessment that can accommodate that diverse knowledge.

3.2. Science-Technology-Society (STS)

A persistent, even if perpetually minority approach to science education focuses on science, technology and society (STS, among other labels) [75-77]. Several curricula (e.g., ChemCom, BioComm, Chemistry in Context, SATIS, 21st-Century Science) have enjoyed measurable success — especially in motivating students and raising interest in and favorable attitudes toward science — although most programs have fallen by the wayside. From the perspective here, such programs notably bring attention to the nature of science at the institutional level and relate science to the broader culture. Whole Science resonates with STS approaches by including the larger social contexts (although it does not emphasize them as primary). That is, as noted above, Whole Science expands conventional views of the nature of science to include the nature of *science-in-society* (NOSIS): from test tubes to YouTube, from the lab bench to the judicial bench [31].

While the goals of science education consistently mention the importance of preparing citizens and consumers, enacted curricula inevitably focus primarily on preparing future career scientists.

STS and Whole Science perspectives both help highlight the bias of mainstream science education for the past century. That is, while the goals of science education consistently mention the importance of preparing citizens and consumers, enacted curricula inevitably focus primarily on preparing future career scientists [16]. Ironically, promoting science involves bolstering public support for science (e.g., funding) and this is achieved by teaching its concrete social relevance through STS and allied approaches. Relevance also helps inspire and recruit students to contribute to science professionally. Any fruitful reform of NOS education will thus need to start by transforming the politics of curriculum decisions, whereby the voices of commerce and professional scientists (prioritizing their own "pipeline") can be kept in check [18]. AAAS's once-monumental Project 2061 [68], the (U.S.) National Research Council's *Framework* [15] and the current PISA framework [12] certainly all embraced this broader cultural vision, and provide a foundational rationale for such change [10].

While Whole Science, unlike most earlier NOS conceptualizations, noticeably incorporates cultural contexts and SSIs, it does not actively encompass the whole STS approach. STS typically engages students in the social as well as the scientific dimensions of the hybrid socioscientific issues. Instruction generally includes ethics and politics. Model classroom activities frequently provide students the opportunity rehearse complex decision-making. Whole Science is not quite so ambitious. It maintains a focus on the science itself as the core. So, it does not ask science teachers to acquire background in social studies, as well. Still, Whole Science may help students understand the distinction between justifying facts and justifying values, the limits of science (and the risks of scientism), and the special case of decision-making under scientific uncertainty (for example). But it does not expect the science teacher to step into perhaps unfamiliar domains where their training and expertise is limited.

What Whole Science does emphasize, however, is science media literacy and the importance of finding trustworthy sources of scientific information to inform public policy decisions. The epistemic concerns about the reliability of scientific knowledge remain paramount, closely linked to the epistemic concerns within the scientific community (Figure 1) [29. 31].

While Whole Science adopts a guarded posture towards the role of science in ethical *justification* or values *choices*, it does not thereby abandon ethics or concerns about social justice—another recent concern raised about conventional views of NOS [78-79]. Indeed, science often has a significant role in documenting the injustices — whether about the causes of gun violence; DNA evidence in reversing wrongful convictions; or exposing the hidden but systematic disparities in exposure to pollutants [28, 58]. The basic facts of inequality or uneven distribution of environmental or workplace risks are based on empirical study, not arguments about fairness. Science does indeed have a role in social justice: by ascertaining the relevant facts of the matter. By focusing on understanding the reliability and uncertainties of the scientific claims, Whole Science extends NOS into the contexts of legal, judicial and policy reasoning [35].

Whole Science also recognizes that the cultural context is an occasion for considering the intersection of science and power — yet another recent concern for NOS instruction [35, 72, 80]. That is, cultural biases may percolate into scientific work, both in terms of what science is pursued (hence, what is known) and in how evidence is interpreted [48]. Science is susceptible to the Naturalizing Error, whereby ideological or cultural norms are subtly (and usually unconsciously) inscribed into the conceptualization of nature [55]. Whole Science thus invites considerations of conflict of interest (funding) and endorses feminist, Marxist and post-Colonialist critiques as integral to understanding the reliability of scientific claims, both within science and in public media (see "Cultural contexts" in Figure 2). Whole Science thereby comfortably accommodates recently widening conceptions of what constitutes preparing students for citizenship, further strengthening the connection between NOS and the general aims of science education.

Whole Science also recognizes that the cultural context is an occasion for considering the intersection of science and power

3.3. Argumentation

Whole Science is oriented to epistemic concerns and the nature of justification. For some, that translates into learning about argumentation [81-82]. Namely, they view justification in science as achieved through argumentation. Moreover, being mindful of arguments and learning how to construct them fosters students being explicit about their thinking. Indeed, sharpening competency in scientific reasoning has been one of the major achievements of this program [26]. So, Whole Science and argumentation are closely allied.

However, argumentation tends to focus on linguistic expressions and writing — a vestige, perhaps, of logical empiricism. Hence, if you equated science with argumentation, you would never need to enter a lab or astronomical observatory or assess the quality of data or evidence. You might easily take confirmatory evidence as justifying your hypothetico-deductive argument, unaware of confounders or alternative hypotheses, and thus be misled. You would not feel the need to check for cognitive biases (such as confirmation bias), or wonder whether your argument was sound reasoning or just hollow rationalization. The focus on argument structure minimizes the need to listen to alternative views or try to reconcile conflicting sets of observations. In short, there are plentiful elements of justification that fall outside argumentation, at all three epistemic levels — observational, conceptual and social [26]. Accordingly, we may warmly endorse argumentation competencies as part of a well stocked epistemic toolkit, but also consider it significantly incomplete, and deficient as a substitute for Whole Science.

Argumentation competencies are part of a well stocked epistemic toolkit.

The theme of argumentation carries into science media literacy as well, where it is often construed in terms of critical thinking [83-85]. There are problems here, too, in conflating argument and justification. For example, an argument may be apparently sound and plausible, but hide flawed assumptions or viable alternatives that only an expert can recognize. It may include evidence that is artfully cherry-picked—again, detectable only with expertise outside the argument itself. Media consumers can be easily misled by the arguments alone. They need foremost to assess the credibility of the person making the argument before considering the argument even worth hearing [22]. Again, Whole Science takes a holistic perspective. It addresses the context of the argument (including the expertise of the speaker, their track record of honesty, conflicts of interest, and so on), not just the argument itself.

3.4. Next Generation Science Standards (NGSS)

Over the last decade, the U.S.'s Next Generation Science Standards (or NGSS) [86] have become a major benchmark for curriculum standards. There, the nature of science was notoriously relegated to an appendix. The NGSS tries to project an image that it respects NOS education—following a modified version of the consensus list. But the structure of the standards revolve instead around "scientific practices," largely intended as a successor concept to NOS. That is, the construct of "scientific practices" is meant to eclipse the need for NOS or contextual ideas about science, while dispensing with the festering debate that seemed to plague NOS discourse. None of the NGSS target competencies refer to Appendix H on NOS.

The concept of scientific practices has some merit. It shifts the focus from abstract understanding to competencies, which can be measured as performance—a stronger approach from an assessment perspective (e.g., [87]. In addition, the focus on practices naturally aligns with inquiry learning, and emphasizes the widely acknowledged importance of learning-by-doing. Whole Science certainly recognizes the virtue of these pedagogical shifts fostered by the NGSS, such as conceptualizing ideas about science as concrete competences that can be assessed [17, 20].

There is merit in shifting focus from abstract understanding to competencies, which can be measured as performance — a stronger approach from an assessment perspective.

At the same time, NGSS exhibits many corresponding deficits. Most prominently, the centrality of practices emphasizes "how," not "why." There is little need for epistemic reflection (despite occasional rhetoric to that effect). Whole Science reminds us that what is needed is not just science inquiry, but also *epistemic inquiry*. Some questions need to be oriented to solving problems about the grounds for reliability. Not just *"how* might you implement an experimental control?", but *"why* do we need controls at all?" NGSS includes "engaging in argument from evidence" as a practice, but it does not elaborate fully on the social dimension, including (as noted above) listening to other arguments and responding to them. NGSS tends to portray argumentation as an endpoint in science, not just as an interactive tool. Another NGSS practice focuses on "obtaining, evaluating and communicating information," with repeated appeals to draw on "reliable media." But it frames this work as within a scientific community, not for the non-expert consumer of science (with all its accompanying challenges). Nor does it acknowledge the non-trivial competence of ascertaining which media are "reliable." None of this is particularly surprising. While purportedly built on the earlier NRC *Framework* —with its concern for educating consumers and citizens [88]— in the hands of Achieve, Inc. (the barely acknowledged consultant-ghostwriter), the NGSS was reoriented to prepare students for scientific careers (as explicitly stated in [86]). "Why" was replaced with "how." The larger context was deftly written out of the standards. A Whole Science perspective makes plain just how much the NGSS document misses. NGSS is a partial approach, oriented to only a small subset of science students in public K-12 education (perhaps only 5-8%). Whole Science is for the whole community, in accord with the widely accepted aims of public science education, as once expressed, for example, in the AAAS's catchphrase, "Science for all Americans." With an STS orientation in mind, we might call Whole Science, "science for the rest of us."

8.5. "Family Resemblance" Approach

Many discussions of nature of science now include as an alternative the "Family Resemblance Approach" (or FRA) [89]. FRA takes its name from an earlier paper philosophy of science which addressed NOS through the lens of the "demarcation problem." The core idea was to apply Wittgenstein's notion of "family resemblance" [61] to science. That is, "science" should not be viewed (philosophically) as a distinct natural kind, delineated by discrete necessary and sufficient conditions. Rather, it is (in modern terms of set logic) a "fuzzy" concept. Not all canonical properties apply to all instances. (For example, most birds fly, but not all. That does not disqualify penguins, kiwis or emus from being bona fide birds.) We get by with a “family resemblance”-type label. Being articulated in the 21st century, it was a somewhat belated and perhaps trivial recognition of the inherent looseness of language and the psychology of concept formation. This acknowledgment was enlisted to inspire an account of the nature of science.

While FRA rejects an essentialist position with regards to science, it nonetheless tends to focus on defining science, as characterized by its inherent “nature.” Whole Science, by contrast, delves foremost into how science works and how its practices relate to the social role of science as a reliable source of knowledge [36-37]. FRA parades its categories — aims and values, methods, social organization, financial and political systems (and so on) — and its pluralism, but the actual content is unspecified: the second problem of NOS education identified by Olson [18]. Of course, any discipline or topic of study has all the same categories: literature, religion, fine arts, education. We could say the same of Rowbotham’s Zeteticism (Flat Earth’s system of inquiry — https://wiki.tfes.org/Zeteticism), homeopathy, or umbrellaology [90]. That does not make any of these pursuits science, nor a source of reliable natural knowledge. FRA thus provides little informative insight into science specifically. FRA may hint that a “scientific” ethos differs from biology to chemistry to earth science. But how does it differ, and why does it matter? How does this inform a citizen’s engagement with science? — that, FRA does not tell you. Like the consensus view, FRA does not explain *why* understanding nature of science matters or how delineating science according to its categories informs the average consumer. FRA thus seems mired in the vestiges of demarcation, trying to define (philosophically) what science *“is*, rather than understand (pragmatically) how the cognitive practices or institutional structure of science yield trustworthy knowledge.

Nor does FRA seem to exhibit structure for actually *learning* about the various methods, models, or social structures (and so on) of science (only that they are diverse)—exemplifying the third problem noted by Olson [18]. One series of sample exercises, presented as paradigmatic in a reference handbook [91], relies on using prior NOS knowledge as the *input* to the lessons, not learning it as an output. Students are asked to fill in the blanks of FRA’s template — as though they presumably know the NOS content already. But this requires vast experience with science and detailed knowledge of its practices across multiple disciplines. For example, preservice teachers were asked to debate whether science has one uniform method, or many. Students are not provided any background or set of cases as a reference. Of course, veterans in science education know that “there is no single scientific method” of the sort so often depicted in textbooks. But how can an introductory student possibly know this without walking through several dozen cases and learning about the method(s) used in each? FRA is an advanced exercise in the philosopher’s problem of the unity (or disunity) of science, not a vehicle for novices to learn the variability of scientific methods. Why should anyone care if there is one method or many (rather than understand how the methods work and with what effect)? In Whole Science, learning is based on case studies — encountered without prescribed categories or NOS principles (more in Section 4).

FRA at least echoed the prior Whole Science model [17-18] by acknowledging a wide diversity of features. For example, both approaches bring sociology of science into NOS, largely peripheralized by educators earlier [92-94]. But Whole Science is unified by its focus on epistemics. It asks: Does this social dimension help the student "understand how science works, to interpret scientific claims in social and personal decision making"? Consider a research lab group that meets regularly at a pub at the end of the week. In FRA, such a consistent "practice" or "interaction" would help characterize science. But for Whole Science you would need to say more before you could conclude that this was significant to the knowledge those participants produced. One group of FRA enthusiasts observed that the biotech industry is full of start-up companies, then noted FRA's category of economic concerns as a reason to argue that *therefore* all biology students should acquire skills in business entrepreneurship — in their science class [95]. In FRA, apparently anything that can be wedged into one of the categories qualifies as science. It lacks a coherent focus, what Olson noted as the second major problem with integrating NOS into the general science curriculum.

Both Whole Science and "Family Resemblance" appoaches highlight the importance of sociology of science, largely disregarded by educators earlier.

Whole Science thus differs markedly from FRA. First, Whole Science explicitly identifies the educational purpose of NOS understanding (not just abstract NOS for its own sake, or assuming it is self-justifying). Second, it uses the cultural role of science as a primary context for delving into the internal processes and external relations of science, and for what counts as pertinent in such discussions. Third, it establishes the relevant content by explaining the epistemic role of each of the various features in an SSI or historical case. For example, it does not parade "methods" as some pre-ordained category, but identifies blinding (for example) as a *specific* method for addressing (*specifically*) observer bias, theory-laden interpretation, or prejudicial peer review. Fourth, Whole Science focuses on functional NOS, whereas FRA seems preoccupied with defining science, so as to reinforce its core idea of a "family resemblance." Where FRA presents a blank template for deconstructing any discipline, Whole Science renders a complete portrait of how science works (as science), wherein it earns its cultural status as a source of reliable and trustworthy knowledge.

4 | Teaching Whole Science

A Whole Science approach aims first to articulate the relevant content of NOS instruction. But it also includes identifying pedagogical methods that help facilitate learning that particular type of content: Olson's third challenge [18]. In some cases, the content strongly shapes the appropriate mode of instruction. In other cases, a Whole Science approach fits comfortably into educational methods whose general effectiveness has already been demonstrated and that are widely endorsed across the discipline. This section elucidates how. Practicing teachers may thus have some models about how to approach teaching NOS content — instructional methods that may differ from how they themselves learned science (possibly years ago).

Teaching ideas about science takes time (because teaching anything takes time.) There is no way around it. Yet if international science curriculum guidelines indicate that nature of science is indeed important [12, 15-16], then teachers need to find a place for it and *manage* the time. The purpose here is to characterize what those lessons might look like, with an aim to make them well motivated, meaningful, interesting, and ultimately valuable (for everyone, including the teachers themselves).

4.1. Case Studies, Narratives and Inquiry

The nature of science may be complex. But this does not mean that NOS lessons have to be so also.

The nature of science may be complex. But this does not mean that NOS lessons have to be so also. Indeed, the structure of Whole Science may make them easier. The simplest way to convey how science works is by exemplification and explicit reflection — through “Whole-Science” case studies or narratives [19-20, 96-99]. Stories of science-in-the-making vividly *illustrate* how knowledge is formed [10, 100]. One does not need to generate some abstract lesson from scratch. The relevant ideas about science and its reliability are inherently exhibited *when science is observed as a process on a human level*. We need only follow the scientists in action [101-102]. Further, the science is already framed as “whole” science, contextualized in its human and cultural context. These connections help motivate learning for students. Case studies are also concrete, so they make immediate sense to a broader range of non-science and less academic students. The narrative format is itself familiar — how we often learn from each other outside a school setting) [103-106]. Different epistemic factors will be found already integrated together (the third sense of “wholeness”), while rising to the surface naturally at various points in the narrative (Figure 3). One could read a book, watch a documentary, or walk through the episode with the students [37]. In general, the strategy here is to teach using samples (small slices or cross-sections) of pre-packaged Whole Science (as described in Section 2.3). In an educational context, the teacher’s main role is then to pose questions, thereby helping students “notice” and extract the lessons through inquiry. Generally, “how do we know this claim is reliable?”

Stories of science-in-the-making vividly *illustrate* how knowledge is formed.

Learning will be enhanced by engaging students themselves in the narrative and the process itself, shadowing the real participants. ...A mentored apprenticeship model takes the place of the now-discredited “discovery approach.”

Of course, such learning will be enhanced by engaging students themselves in the narrative and the process itself, shadowing the real participants [107]. (What is it like to work alongside some historical scientist as they make a famous discovery? Here, a mentored apprenticeship model takes the place of the now-discredited “discovery approach” [37]. So, an appropriate narrative addresses science at the scale of human actions, choices and decisions. The narrative helps frame the core epistemic problems (as experienced historically). Setting the narrative on hold, the teacher poses a problem to the students to solve on their own [25, 97]. (Here, the teacher chooses the appropriate discussion format — small-groups, reflective writing, whole-class sharing, overnight exercises.) Each class develops their own solution: the epistemic concepts are thereby “owned” by the students. Then the narrative resumes, in part revealing how the problem was addressed historically (sometimes successfully, sometimes not!). This is *epistemic inquiry* as opposed to familiar science inquiry that usually takes place in a lab space [97]. An example of a series of questions that form the skeleton of a narrative is provided in Figure 6: the case of Carlos Chagas and “The Railroad Workers’ Disease” [109].

Epistemic inquiry is based on problematizing the process of developing knowledge.

Epistemic inquiry is based on problematizing the process of developing knowledge. The teacher’s role is to recover the questions that originally motivated the epistemic concepts (Appendix). That often emerges from the case itself (when viewed in the present tense, as science-in-the-making). There,

Figure 5. A sample of questions in a Whole Science inquiry narrative: “The Railroad Workers’ Disease” [109].

	Questions	**Epistemic Theme**
1	As President of the Central Brazilian Railroad Company, you encounter a plea to help workers plagued by disease and unable to work. *What are your concerns, and what actions are available to you?*	• The role of political and economic factors in supporting scientific research
2	The disease is very similar to malaria, but not in all respects, as depicted in a table comparing the symptoms. *How would you determine if the railroad workers’ disease is a variant of malaria or a different disease entirely? What additional information would you like to collect? What criteria would you apply before seeking an alternative treatment or remedy?*	• The role of analogy • The relationship between laboratory studies and field studies
3	A local railroad engineer suggests that a local "kissing bug" may transmit diseases. *Should you take his suggestion seriously? Give at least one reason for heeding his advice and at least one reason for doubting it. What could you do to investigate the information further?*	• The role of personal background, motivations and skills • The role of local or anecdotal knowledge versus systematic investigation • The role of chance or contingency
4	Protozoans are indeed found in the local bug and also in a local population of marmosets (small primates), but the marmosets are not diseased. *How might you determine if the forms observed in the bug and the marmoset are different species or variant life stages of the same species? What expertise and resources do you need for this investigation? How will you secure them?*	• The role of analogy • The relationship between laboratory studies and field studies
5	When the bug bites and infects the marmosets in the lab, they become diseased. *How can you confirm if the disease in the marmosets is the same as that of the railroad workers?*	• The relationship between laboratory studies and field studies
6	Several efforts to find the protozoan in human disease patients fails. *Should the blood investigations be abandoned or continued? If so, for how long? What factors guide your decision?*	• The role of patience and persistence • The relationship between laboratory studies and field studies
7	No protozoan is found in a diseased child, until her condition worsens and her blood is tested again. The “kissing bug” protozoan is finally found in humans. *In what ways does this finding change the course of the investigation? How might such unexpected events affect how you plan and conduct scientific investigations?*	• The role of chance or contingency • The role of patience and persistence
8	*Is the presence of the protozoan T. cruzi in this one patient's blood sufficient to show that it causes the disease? If not, why not? How else might you link together the relevant evidence about the protozoa in kissing bugs, patients' blood, and other animals?*	• The role of chance or contingency • The relationship between laboratory studies and field studies • The role of collaboration • The role of analogy
9	Blood from several diseased humans is injected into lab animals and many become diseased, even without exposure to the “kissing bug.” *What do you conclude from these experiments, in the context of all the other evidence gathered through Carlos’s work?*	• The role of analogy • The relationship between laboratory studies and field studies
10	Through multiple parallel investigations, Chagas makes a “triple discovery”: he has identified a new disease, the microorganism that causes it, and the animal that transmits it. *What types of scientific work were needed to generate this evidence, and how was each important?*	• The role of personal background, motivations, skills and collaboration • The role of local or anecdotal knowledge versus systematic investigation • The relationship between laboratory studies and field studies • The role of chance or contingency • The role of patience and persistence • The role of political and economic factors in supporting scientific research
11	*Imagine the impact of Chagas's investigations and conclusions on the science of studying diseases. How might understanding the history of this one case shape public policy on funding science and using its results?*	• The application of research knowledge to public health • The role of political and economic factors in supporting scientific research
12	*Why and how are awards important (and from whom)? What level of recognition does a discovery like this deserve?*	• Incentives and rewards in science
13	Review of and explicit reflection on all nature of science themes	all of the above

participants are blind to the outcome and have to negotiate their way through various epistemic challenges. The student may hear the refrain, "how do we know this?" And, equally perhaps, "how do we know that we are not mistaken?" [41]. One thematic aim is to nurture a long-term disposition to ask epistemic questions, among both teachers and students. It's that simple.

There is an art to crafting good open-ended inquiry questions.

Well, perhaps it is not *that* simple. There is an art to crafting good open-ended inquiry questions, at just the right level of accessibility and challenge for a particular group of students. They must be truly open, to avoid succumbing to stereotypes and preconceptions. There is also some skill involved in assembling a compelling narrative—although we all tell stories and have personal styles for engaging our audience (humor, suspense, conflict, personal struggle, shifting point-of-view, characterizations, gestures). So, initially, the novice might elect to use (or adapt) someone else's prepared case study. Plenty are available now (for eight dozen in biology, see [108]). Three prepared cases, in particular, are valuable as an introduction because they are accompanied by explicit commentary on the pedagogical structure of the lesson, and provide guidance about how to assemble other such cases:

- "Alfred Russel Wallace & the Origin of New Species" [24, 110];
- "Christian Eijkman & the Cause of Beriberi" [21, 111, Figure 4]; and
- "The Vaccine Skeptics of 1721" [25, 112].

A large number (from numerous disciplines) are also summarized (and the format discussed further) in [19].

4.2 Managing Cases

Lessons involving ideas about science are exceptional in that, unlike much other science content, they can be generalized across a broad domain. Case studies can often be addressed economically, in one class (or extended to 2 classes for more depth). But consider just four classes per year, compounded by twelve years? (Then consider, perhaps, a more generous allowance of one per month, or as a customary transition between multi-week units—still a modest investment of teaching time.) Learning builds, filling in an understanding with increasing scope and resolution. Whole Science provides, in part, a framework for unifying those lessons across many months or in the long-term. Historical cases solve that problem—and educators who reflect on their ears.

Case studies may be historical or contemporary. Each has advantages and disadvantages.

Case studies may be historical or contemporary. Each has advantages and disadvantages [19, 47]. Contemporary cases have an aura of here-now relevance, but they are often unresolved, making it difficult to learn the epistemic principle, which may be evident obvious only in the long term. Historical cases solve that problem — and educators who reflect on their own learning about the nature of science typically report being informed most by history. (History applies equally to misinformation, such as the cases of vaccines (1720s), the reception to *Silent Spring* (1963), the New Madrid earthquake (1991) or eugenics (1920s) — see http://shipseducation.net/misinfo). But the cases may feel remote if the story is not well chosen or told well. Still, teachers often already know a bit about a few historical episodes—and this can be a valuable starting point. You do not need to be a historical scholar to have learned enough to manage just a handful of cases effectively. These may be placed amidst other, perhaps more familiar, lessons which involve students in their own inquiry and use explicit reflection about their experience. Again, each has benefits and limitations.

Another responsibility of the teacher is the selection of appropriate cases, to address the diversity of epistemic concepts with a Whole Science perspective. Learning about the many factors in reliability of knowledge is not achieved in one lesson or a concentrated sequence of exercises. Any particular case will tend to highlight only a small handful of concepts (perhaps 3-7) that were especially consequential or visible in that episode [113]. The teacher's responsibility is, in part, to select a series of cases that, over time, will help cover NOS at several levels of scientific practice and in various circumstances (Figure 2, Appendix). The set of cases should complement each other, although noticing epistemic features echoed in successive cases can also be important. Again, this invites a flexible bottom-up menu approach, rather than the prevalent top-down, checklist approach that stifles teacher autonomy, creativity and motivation. Whole Science is commensurate with locally informed, teacher-centered curriculum decisions—rather than uniformity imposed by a centralized authority [32, 72].

The teacher's responsibility is, in part, to select a series of cases that, over time, will help cover NOS at several levels of scientific practice and in various circumstances.

4.3. Teacher Education

Teachers will need to become familiar with this style of teaching, which may differ from how they themselves were taught, especially with the role of open-ended discussion. Most will need to participate in and experience case study learning several times. In addition, they need to learn how to pose well framed epistemic questions. Not science inquiry, but epistemic inquiry: the "why" questions that delve into context and justification (not the "how" questions of scientific practices). Still, this requires far less of teachers than mastering the history, philosophy and sociology of science (or ethics or social studies) before one can begin to teach science in context.

Prepared case studies offer another advantage. They can be occasions for teacher and students to *learn together*. That is, we cannot expect all teachers to arrive in the classroom fully versed in every dimension of science — the potentially formidable vastness of a Whole Science perspective. Teacher education is also important — Olson's fourth challenge [18]. We must conceive of a system whereby teachers learn the ideas about science, too. It is part of professional development, perhaps. A work-in-progress. So, adopting Freire's posture towards dialogical education [72], we may invite teachers to work together with the students, as co-learners and collaborators. One of the chief features of a narrative of science-in-the-making is that it is blind to the outcome. So the teacher should always adopt the student's dilemma of not knowing the answer in advance (no spoilers, no biased hints, no anachronistic cheating). Perhaps we can foster a culture where it is perfectly acceptable for the teacher (who already has the advantage of much more experience with science in general) to work alongside students as they figure out epistemic principles together, as a team? That might be ideal.

Adopting Freire's posture towards dialogical education, we may invite teachers to work together with the students, as co-learners and collaborators.

5 | A Future for Whole Science

A Whole Science approach aspires to convey the practical value and relevance of nature-of-science education, largely by contextualizing it in contemporary SSIs and vivid historical examples. Education that addresses the reliability of scientific claims in public discourse is essential. At the same time, a Whole Science perspective acknowledges that the forms of that knowledge and the ways to achieve it in the classroom are highly variable and flexible. To echo an earlier statement, one should refer to “a” Whole Science approach, not “the” Whole Science approach. There need not be any standardized, narrowly defined, prescribed curriculum for students to learn how science works. Indeed, while the teacher should feel responsible for teaching ideas about science, they should also enjoy the professional freedom to teach it in a way commensurate with their personal strengths and style of teaching and their students’ needs and interests.

This report, in particular, has addressed some of the challenges that have been observed in enacting such curricula in practice, as described by Olson [18]. First, it strongly connects the aims of science education to the details of reflecting about science in context (Section 1). Second, Whole Science articulates the concepts and unifies them into a coherent vision (Section 2; Figures 1-3; Appendix). Third, teachers are provided models to guide classroom instruction (Section 4.1; Figure 6). Fourth, there are easy ways to prepare teachers with the basics, along with a strategy that allows them to continue learning on their own and with students (Section 4.3). This report should thus facilitate realizing this essential dimension of science education. Now, we must trust policymakers to exhibit the courage to establish curricula standards that reach beyond corporate or narrow economic interests and affirm the civic and cultural role of science education. The focus must extend beyond recruiting or training future scientists to developing citizens and consumers with the skills needed to analyze scientific claims intended to inform personal and public decision making. Notably, that will include designing assessments that reflect these aims [12, 17].

A Whole Science approach resonates with the lingering tradition of education through mentored apprenticeship. Here, the aim may not be to acquire the skills of *doing* science, so much as *observing* how science is done so one can interpret its claims. Students learn how science works by participating vicariously in historical episodes of discovery or debates about science in a societal context. As observers, they can appreciate the process as a whole. The purpose of this essay—a synoptic review of sorts—has been to consolidate a large body of diverse work related to a Whole Science perspective of science education, which includes the “whys” of knowledge, in addition to the “whats” and “hows” of science.

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Where will the resources come from? Many lessons have already been developed. As noted earlier, any reflection on the process or context of science can be worthwhile — science documentaries, podcasts, autobiographical books by scientists, journalists’ feature articles, and more. Educators, too, have organized materials into numerous historically based case studies that critically also include inquiry (Figure 7). They range from the surprising complexity of measuring atmospheric carbon dioxide [132] or the puzzle of classifying hydra as plant or animal [117], to interpreting herbal remedies by Native Americans [118] or exploring the religious context of the 1919 eclipse expedition to document the bending of light by the sun (according to relativity theory) [129]. They include exploring the cause of earthquakes based on the great 1905 San Francisco quake [124], and considering radioactivity in the episode of "the radium girls" [124]. Some activities are historical simulations, with many roles for different students — prime occasions for understanding scientific debates. There are also many collections of cases available online, across various fields (Figure 8). Internet search engines and AI programs now facilitate the teacher's work in finding available resources. Of course, teachers often have favorite episodes from the history of their field and may be inspired to assemble their own inquiry cases [21, 24, 25].

Figure 7. A sampling of historical case studies reflecting a Whole Science perspective.

BIOLOGY

- *Alfred Russel Wallace & the Origin of New Species* [110]
- *Carleton Gajdusek & Kuru* [114]
- *Modeling Mendel's Problems* [115]
- *Sickle-Cell Anemia & Levels in Biology*, *1910–1966* [98]
- *King D Carlos, A Naturalist Oceanographer* [116]
- *Abraham Trembley and the Creature that Defied Classification* [117]
- *Interpreting Native American Herbal Remedies* [118]
- *Henry David Thoreau & Forest Succession* [119]
- *Debating Rachel Carson's* Silent Spring*, 1963** [120]
- *Darwin, the Copley Medal and the Rise of Naturalism** [121]

CHEMISTRY

- *Amodeo Avogadro & His Weight–Volume Hypothesis* [122]
- *Bunsen, Kirchoff & the Origin of Spectroscopy* [123]
- *Death by the Numbers: The Radium Dial–Painter Tragedy* [124]

PHYSICS

- *Contested Currents: The Race to Electrify America* [125]
- *Charles Du Fay: Explorative Experiments* [126]
- *Robert Hooke, Hooke's Law & the Watch Spring* [127]
- *William Thompson & the Transatlantic Cable* [106]
- *Electromagnetism & the Telegraph* [128]
- *Arthur Eddington & the Solar Eclipse Expedition of 1919* [129]
- *The Committee on Uranium, 1939** [130]

ASTRONOMY

- *Debating Galileo's Dialogue: The 1633 Trial** [131]

EARTH SCIENCE

- *Charles Keeling & Measuring Atmospheric* CO_2 [132]
- *Evolution of the Theory of the Earth* [133]
- *The 1906 San Francisco Earthquake* [124]
- *Debating Glacial Theory** [134]

*role-play simulation

Figure 8. A sampling of case study collections available online.

- *The Story Behind the Science* — storybehindthescience.com [100]
- The Minnesota Case Study Collection — shipseducation.net/modules [19]
- The Project StoryTelling — www.science-story-telling.eu [104]
- *Doing Biology* — doingbiology.net [97]
- History and Philosophy in Science Teaching — www.ew.uni-hamburg.de/einrichtungen/ew5/didaktik-physik/ projekte-abgeschlossen/bis-2015/2008-2010-hipst.html [126]
- GeoScience Resources — Historical Case Studies — www.dolphin-geoscience.ca/categories/historical-case-studies [124]

Echoing all the details and resources detailed in the sections above, one may distill the essentials, closing with “Whole Science in a Nutshell”:

“Whole Science in a Nutshell”

- Link education about how science develops reliable knowledge to the purposes of science education generally and use that context to select (and provide a pedagogical rationale for) particular epistemic lessons.
- Focus foremost on what students need to understand to assess the reliability of scientific claims relative to informing personal and public decision making.
- Use a broad, inclusive approach to understanding how science works. Rather than rely on a predetermined, truncated list of factors, let the sociocultural context of each case determine the relevant feature.
- Embed epistemic lessons in authentic cases and approachable narratives, whether from history or contemporary cases. Integrate them with conventional science content.
- Use epistemic-inquiry questions to engage students in open-ended problem-solving and discussion. Motivate these inquires using their concrete historical or contemporary context. Consolidate lessons by facilitating student explicit reflection on what they have learned, citing specific case details.
- Review the spectrum of epistemic concepts and dimensions at multiple levels to ensure balance in the selection of cases and exposure to diverse features over time.
- Embrace the complexity of scientific practices and socioscientific issues. Leverage the relevance to engage in lessons on how to manage complexity and focus on relevant dimensions.
- View public science communication as a relevant extension of the epistemic problems (science media literacy).
- Let students and teachers explore and learn together how science works and ensures the reliability of its claims.

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Appendix

A Partial Inventory of Epistemic Concepts [20, 26]

Epistemic Level	*Epistemic Dimensions*	*Sample Epistemic Concepts*
OBSERVATIONAL	**Observations and measurements**	• Verifiable information versus values • Systematic study (vs. anecdote) • Relevant observations • Accuracy, precision / measurement uncertainty • Completeness of data • Proxy variables • Material contaminants
	Experiments	• Controlled experiments • Blind and double-blind studies • Sample size and replicates • Randomized sampling • Documentation (lab notebooks)
	Instruments	• New instrument technology • Calibration • Artifacts • Models and model organisms • Ethics of human-subject experimentation
CONCEPTUAL	**Forms of reasoning**	• Causation vs. correlation • Probabilistic inference • Statistical analysis of uncertainty • Alternative explanations • Heuristics • Logical fallacies • Models • Robustness
	Creativity & history	• Consilience with established evidence • Analogy • Interdisciplinary thinking • Imagination and creative synthesis • Conceptual change
	Human dimensions	• Motivations for doing science • Confirmation bias/role of prior beliefs • Availability bias • Flaws in probabilistic reasoning • Motivated reasoning
	Cultural contexts	• Gendered perspective • Race-based perspective • Class/political-based perspective • Religious/ideological perspective

Epistemic Level	*Epistemic Dimensions*	*Sample Epistemic Concepts*
SOCIAL-LEVEL	**Economics/funding**	• Choice of research question • Conflict of interest
	Institutions	• Collaboration and competition among scientists • Forms of persuasion • Peer review / forums for open debate • Academic freedom / conflict of interest • Consensus panels • Social responsibility of scientists
	Publication & peer review	• Norms for handling and sharing scientific data • Pre-registration of data analysis methods • Nature of graphs • Publishing conventions • Pre-publication peer review • Professional credibility • Fraud or other forms of malpractice • Diversity and critical consensus
PUBLIC (COMMUNICATIVE)	**Credibility**	• Verifiable credentials • Track record of honest reporting • Institutional framework • History of responsible gatekeeping • Conflict of interest / neutrality
	Expertise	• Record of past achievements • Educational background • Experience • Peer recognition and leadership • Peer certification • Consensus of relevant experts
	Deceptive tactics	• False experts • Identity politics and social emotions • Blind skepticism • Repetition • Style over substance
PERSONAL AND PUBLIC DECISION-MAKING		