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ARTICLE

Is Science "Tentative"?

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Abstract

A major feature of the nature of science (NOS) has conventionally been that "science is tentative." What exactly does this phrase mean, and is it clear and justified? How does this view relate to assessing the reliability of scientific claims in the media, relevant to personal decision-making and public policy? Despite widespread rhetoric, science is not systematically "self-correcting," although errors can be and often are corrected. We need to clarify for students precisely how scientists err, and how they resolve their errors, as a basis for judging when or how to trust particular claims. That requires inquiry learning into NOS, based on cross-sections of Whole Science, not lists of general NOS principles, such as "tentativeness."

Keywords Nature of science · Tentativeness · Error · Self correcting · Covid · Whole Science

A canonical educational view about the nature of science (NOS) is that "science is tentative" (Lederman & O'Malley, 1990; Lederman et al., 1998; Mueller & Reiners, 2023). Tentativeness has been a benchmark of the so-called consensus list (McComas & Clough, 2020; McComas & Olson, 1998; McComas, 1998, 2020b; Osborne et al., 2003) and a prominent feature of the heavily used VNOS instrument (Abd-el-Khalick et al., 2024; Lederman et al., 2002). There are important core lessons for citizen-consumers about scientific change, uniform progress, error, error correction, uncertainty, confirmation bias, and varying degrees of justification. But the language and the underlying concept of "tentativeness" are, I contend, inappropriate benchmarks and even misleading and counterproductive. Here, I review the historical context of this dimension of NOS education, assess the appropriateness of "tentativeness" as a term, and explore alternatives to framing the targeted understanding. That, in turn, leads to reflections on widely adopted approaches to NOS education, customarily centered on lists of general, abstract statements, such as "science is tentative." Again, I present an alternative that basically shifts from rote conceptual NOS content to NOS *practices* or NOS *styles of thinking*.

By way of engagement, I begin with a mundane scenario. Imagine a student (or consumer or citizen) early in the COVID pandemic. Advocates urged trust in science. A month into the pandemic, I shared with a neighbor the epidemiologists' forecast that

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one-half to two million people would die from the virus over the next few years. She was aghast. That was too implausible to her (how could anyone know that in advance?). In this case, the dire alarm was indeed well informed and sadly accurate. That was the power of expert epidemiological modeling. What would have been the upshot of viewing this forecast—hardly tested—in the context of the principle that "science is tentative"? Would a cautious view of scientific (un)certainty have impressed her with the seriousness of the looming public health crisis? In those days, experts also said that the virus was transmitted by contact. Fear and frenzy followed. Hand-sanitizer sold out everywhere. Well, that claim, by contrast, turned out to be mistaken: the virus was airborne, carried in respiratory droplets. Public confidence in science was widely shaken. Would reminding them that (after all) "science is tentative" have helped? Many consumers thereafter exhibited skepticism, leading to widespread distrust for the experts' claim that hydroxychloroquine (HCQ) was ineffective at either preventing or treating COVID. The same discounting of science occurred later regarding the roles of social distancing and masking in controlling the spread of the disease. The early history of COVID seems to me typical of the challenges of controversial socioscientific issues (SSIs) that educators cite as a main context and reason for learning about NOS (e.g., Maia et al., 2021; Moura et al., 2021; Wong et al., 2008). And yet I think this brief analysis shows that knowing about the "tentativeness" of science would not have been helpful at all. Merely knowing that "science is tentative" does enable anyone to differentiate the cases where science is reliable from those where it is less certain. Nor does it tell you *why* some scientific errors in this case originally seemed reasonable. Let the puzzles of this historical episode be a discrepant event *about NOS education*, that may lead us to reconsider our preconceptions and explore new, alternative perspectives?

1 A Historical Prelude

While the term "tentativeness" is ubiquitous in science education, it can be interpreted in many overlapping, yet divergent ways. Does it refer to caution and provisional claims? Does it label ineliminable uncertainty, or conceptual change, or both? Is it about the contingencies of history and discovering earlier errors? A core strength or fatal weakness of science? All can be found in the science education literature and in public perceptions of science.

A brief historical excursion may help contextualize the problem. Yes, there are important lessons about NOS involving scientific change, errors, science-in-the-making, controversies, and the reliability of particular scientific claims. And they are basic to the aim of preparing citizens and consumers to participate in the personal and public policy decisions informed by science (e.g., National Research Council, 2011; Rudolph, 2024). What are these lessons and how did they become important in science education?

Prior to 1962, the philosophical outlook was largely positivist. Scientific knowledge seemed based on discrete facts, independently verifiable by observation and/or experiment. Science seemed to progress as facts accumulated and were synthesized into increasingly abstract general theories. For example, Newtonian physics was historically superseded by the wider and more complex relativistic physics. Mendelian genetics could be reduced to the mechanisms of molecular and cellular biology. Chemical structures and reactions could be reduced to atomic structure, electrons, and valence theory. And so on. Accordingly, science seemed to converge on the truth. These epistemic perspectives are still important today, as they often reflect unschooled beliefs. Many students idealize knowledge intuitively as simple and certain (or not) (e.g., Schommer, 1990). Similarly, inherent teleological tendencies tend to frame science as inevitably growing and improving (e.g., Keleman & Rosset, 2009).

All that changed with Thomas Kuhn's (1962/1970) work on *The Structure of Scientific Revolutions*.[1] First, Kuhn showed how theoretical language and assumptions permeated conclusions. For example, the concept of mass was not consistent from Aristotle to Newton to Einstein. Same term, different meanings in context. Interpretations of the evidence itself could differ, based on a more holistic disciplinary matrix of methods, ontologies, and interrelated concepts. Lavoisier and the earlier phlogistonists parsed the world in "incommensurable" entities. So, no more isolated facts as piecemeal benchmarks. Second, when new ideas arose, judgments were mired in confirmation bias (or "paradigm-induced expectations"). Problematic data might be construed as "anomalous" rather than as discounting the legitimacy of the theory. Based on historical studies, Popper's ideal of falsification was a naive myth (especially as a "demarcation criterion").[1] So much for evidence as the sole and ultimate arbiter. These observations contributed to a third insight: that sometimes new theories introduced new ways of organizing phenomena and doing science that did not merely add to, or encapsulate, the former. That is, some theories replaced—or displaced—earlier ones, leading scientists to jettison some once-accepted concepts, hence scientific revolutions. We no longer think in terms of chemical affinities, humoral medicine, heat as a substance, electrical fluids, vitalistic forces, fixed continents, a steady-state universe, and so on. Indeed, some of these episodes are haunted by loss of explanatory power (appropriately dubbed "Kuhn-loss") (e.g., Laudan, 1977). So, science does not always progress uniformly. In sum, logical empiricism yielded to a more nuanced post-positivism.

Kuhn's revelations inspired a wave of historically based philosophical work on theory change and "theory competition" in science, with various efforts to rescue the notion of progress (work by Imre Lakatos, Larry Laudan, Stephen Toulmin, Mary Hesse, David Hull, and others). They articulated the many ways that controversies emerge and are resolved (e.g., Donovan et al., 1988; Engelhardt & Caplan, 1987).

Subsequently, sociologists of science probed the cultural contexts that shaped scientific thought, highlighting various forms of bias (nationalistic, gendered, racist, class-oriented) (e.g., work by David Bloor, Barry Barnes, Donald Mackenzie, Steven Shapin, Simon Schaffer, Harry Collins, Trevor Pinch, Karin Knorr-Cetina, Sharon Traweek, Brian Wynne, and others). Feminist historians added to the mix (e.g., Londa Schiebinger, Donna Haraway). It became clear that racist theories of intelligence, sexist interpretations of female anatomy, and class-oriented claims about genetic conditions all haunted science for decades. Science suddenly seemed far less objective and far less stable than before. The sociologists also delved into the dynamics of scientific controversies, exposing the significant role of values, interests, and politics, echoing Kuhn's view that science was not so pristine or purely logical as once imagined. For some, the question became whether anyone could rely on science ever again.

Science was still largely empirical and experimental. But not necessarily exclusively so. It was definitely *not* simple, *not* absolutely certain, and *not* theory independent. Progress was *not* guaranteed. And its claims were certainly *not* permanent for all time. The implications for the ordinary consumer or citizen were obvious. With all these qualifications and infelicities, which scientific claims could you rely on? How would you know?

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[1] One can readily acknowledge Kuhn's precursors and others in a similar spirit: Ludwig Fleck, Norwood Hanson, Pierre Duhem, Willard Quine, Alexandre Koyré, Gerald Holton, and others.

Educators took notice, of course. By the late 1960s, they began to speak regularly of the fluidity of scientific knowledge. It became a component of educational characterizations of "the nature of science" and has persisted ever since (Lederman et al., 1998). The current instantiation of the concept—as conceived in the so-called consensus list and the VNOS assessment—is labeled "tentativeness" (Lederman et al., 2002; McComas & Olson, 1998; McComas, 2020, 2020b; McComas & Kampourakis, 2020; Mueller & Reiners, 2023). The influential Next Generation Science Standards say merely that "scientific knowledge is open to revision in light of new evidence" and that "scientific findings are frequently revised and/or reinterpreted based on new evidence" (Lead States, 2013, Vol. 1, pp. 82, 110, 237, 266, 269, Vol. 2, p. 99; a mention of tentative appears once, on p. 262).

This is the background to the current challenge: how do we convey the nature of scientific change, while not succumbing to nihilistic relativism? How do we honestly convey scientists' errors and biases, while also conveying the value of scientific claims in informing personal and social decision-making?

2 What Does "Tentative" Mean?

The first (but not the ultimate) question I address here is whether characterizing science as "tentative" is an appropriate way to express the essential lessons of scientific change and their implications for reliability and progress in science.

So, let us imagine the naive student who, presented with this term, searches the internet for a definition. They will encounter such phrases as:

not certain or fixed; provisional
done without confidence; hesitant
not fully worked out or developed
hesitant, uncertain
attempted, provisional, done as a trial
not certain or agreed
unsure; not definite or positive
not definite or set, not confident

There are hints of the theme of "subject to change" ("provisional"). But the primary themes are hesitancy and uncertainty. Such a posture may have described Linus Pauling's proposal for a triple helix structure for DNA in 1953. Although published, it was explicitly speculative: as in, a *tentative* hypothesis. But that would hardly describe Watson and Crick's proposal, a few months later, of a double helix structure, which provided several lines of evidence and has been cited repeatedly as a masterpiece of scientific writing. Nor again in 1962, after the DNA's semi-conservative replication had been confirmed in "the most beautiful experiment in biology," and a Nobel Prize awarded. Nor would we be comfortable suggesting that atomic theory or cell theory or plate tectonics are uncertain, advanced hesitantly or without confidence. Nor is that interpretation appropriate for the IPCC's claims about anthropogenic climate change. There may be uncertainties about the *degree* of expected warming, or the *range* of model predictions, but hardly about the fundamental understanding of planetary warming itself. Levels of certainty (or confidence) vary, depending on the depth of testing and the rigor of the evidence. Contemporary science or science-in-the-making differs vastly from textbook science. There is no single level of "tentativeness" for all scientific claims. While teachers may try to finesse the message, the term "tentative," implying inherent hesitancy and uncertainty, can be grossly misleading.

For this reason, perhaps, the "tentative" label is often now expanded as "tentative, *but durable*," or long-lasting (e.g., McComas, 2020a, 2020b, p. 59). However, this hardly solves the problem. Rather, it only serves to confuse students: Is science tentative, or durable? Hesitant, or confident? Uncertain, or well-vetted? Provisional, or stable? Perhaps science can be both, on different occasions. But that is not very helpful when you encounter a *particular* scientific claim—relevant to public energy policy, say, or to choosing an eco-friendly product. You want to assess its specific level of reliability. Once again, the general claim is uninformative.

Moreover, duration is not a measure of reliability (contrary to Mueller & Reiners, 2023, p. 1819). The appropriate gauge (as noted above) is the depth and completeness of the justification. For example, have investigations been *rigorous*? Has the testing been *complete* (across the concept's entire domain)? Is the evidence *robust* (from multiple laboratories and/or multiple independent forms of investigation)? What possible *sources of error* have been fully probed? Have the claims passed scrutiny from *diverse theoretical and critical perspectives*? Consider the case of the viceroy/monarch mimicry, cited as an illustration of Batesian mimicry for over a century—and frequently presented in biology textbooks. "Durable"? In the 1990s, someone finally tested whether viceroys themselves were distasteful. They were. The striking resemblance of the butterflies exemplifies Mullerian (not Batesian) mimicry. The mistaken claim endured for over a century, absent a simple test (Ritland & Brower, 1991). Longevity, alone, is not relevant to science. This is just poorly informed philosophy.

The broad generalities that "science is…" are not very helpful in the context of current scientific claims in the media. Different claims fall across the spectrum of relative reliability. Some claims—especially those related to incomplete science-in-the-making (typical of many SSIs)—may not yet be fully vetted by adequate testing. Some claims may be hotly debated by the relevant experts, not yet resolved. Yes, a consumer might crudely consider these "tentative" and should approach them with caution. But most of the science found in textbooks, or presented by an NIH consensus panel, is hardly at that uncertain stage. Those concepts might be considered durable. The citizen-consumer's chief problem is not describing science in general, but in assessing *particular* claims. What students need to navigate these circumstances is knowing how to *differentiate* the reliable from the unreliable, the "durable" from the "tentative"—and abstract pronouncements about "the nature of science" (writ large) cannot do this. The relevant questions are: *When* is science to be treated as tentative? *When* as durable? These are not subsumed in a general statement that "Science is…".

More recently, the (devastatingly) obvious ambiguities of "tentative-but-durable" have been coupled with a reassurance that "science is self-correcting." The contention is that, ultimately, one need not be too concerned about whether science is tentative *or* durable, because scientists will eventually find and fix their errors. The clear implication is that if mistakes appear, they are expediently eliminated: hence, at any given moment, one can accept its claims as true (e.g., Kampourakis, 2016; Lederman et al., 2020; McComas, 2020b; McComas & Kampourakis, 2020; Yacoubian, 2020). Indeed, this is a familiar trope of science advocates, including many philosophers, scientists, and editors of the journal *Science* (e.g., Alberts et al., 2015; McIntyre, 2019; McNutt, 2020; Romero, 2016; Tharp, 2023; Zimring, 2019). Unfortunately, it harkens back to a pre-Kuhnian outlook, where any public scientific claim is presumably safeguarded from error and immune to future change. But the appeal to self-correction whitewashes over vulnerabilities to many sources of error.

The history of science is filled with erroneous concepts and theories—black bile, phlogiston, mesosomes, a single human evolutionary lineage, hysteria, the elements nebullium and coronium (along with some 200 others), a universal genetic code, the impossibility of diatomic elements, diluvial geology, Pluto and Vulcan as planets, a central dogma of molecular biology, and more. While many errors are ultimately found and remedied, there is no systematic mechanism or guarantee of timeliness for such corrections (Allchin, 2026).[2] As a result, some errors persist for years, decades or even centuries. Some "corrected" errors led to other errors because the real error is not properly identified. Some errors precipitate other (downstream) errors, based on the first, before they are corrected. Some errors are corrected by individual scientists, only to be rejected by the scientific community. Some errors are corrected only after long intervals, by happenstance. The allure of self-correcting mythos as a guarantor of scientific authority at any given moment is potent, but ill informed (Allchin, 2015). That is a central notion that the NOS principle of "tentativeness" is supposed to convey. Asserting that science corrects itself, without explaining fully how or when, is grossly misleading and not helpful to students as future consumers or citizens.

In short, the meanings of "tentative," as well as "tentative, durable and self-correcting," are too vague and misleading to contribute to the aim of preparing consumers and citizens to engage with *specific* scientific claims in the media (as in the COVID case), or to assess their *degree* of reliability. It is largely hollow rhetoric that students should trust science, no matter what, while providing an "escape clause" if (when) errors are found.

3 The Specter of Scientific Change

One could just say that science is "subject to change," or "open to revision." Presumably that's what "tentative" is *supposed* to mean, based on the brief history above. But this framing, without further elaboration, can be problematic, too. Without explaining the reasons for change (and the reasons for earlier errors), or acknowledging the varying nature and depth of justification, the proviso can potentially backfire. Ironically, the specter of future change may be enlisted as a reason to *reject* consensus science. Exploring this didactic challenge will help us delve deeper into the problems of how NOS education itself is conceptualized.

Clough has noticed "the mistaken view that easily follows from teaching that science is tentative"—namely, "how this can fuel disregard for well-established science ideas important in socio-scientific decision-making" (2020, p. 280) (similarly noted by Allchin, 2013; Cobern et al., 2022; Hodson & Wong, 2017). "Tentative" implies not yet stabilized, hence *unreliable*. Indeed, naysayers of certain scientific claims have weaponized the notion of scientific change against science. Consider this letter to the editor in a newspaper, challenging Dawkins' published comment that "Evolution is a fact, as securely established as any in science":

> Perhaps the wisest science teacher I know told his class that science proves nothing true; it can only prove things false. Until something is proven false, we can only assume it to be true until further notice. Science has proven wrong in the past. Remember Pluto? When I was in primary school, everyone knew it was a planet. Now, kids are taught that it's not. Science is constantly updating itself, and things that we knew for certain 20, 50, 100 years ago will eventually be refuted. (Juel, 2011)

So, since all science "is constantly updating itself" (Pluto and other cases), one is freely entitled to dismiss evolution, as well, as equally susceptible to change. That argument template was echoed in another letter:

> Medical personnel and journalists are scratching their heads wondering why parents don't believe the experts when they say vaccines don't cause autism. For insight into this skepticism, just turn the newspaper page to the article "Further study of food dyes is urged." For years, experts have assured us that there is no link between food dye and childhood hyperactivity, but now the FDA says that "hyperactivity and other behavioral problems may be exacerbated by food dyes." (Johnson, 2011)

Here, the case of updated science on food dyes has served as an analogy to justify rejecting the totally unrelated claims about the safety of vaccines. The idea of scientific change can easily be reconfigured to malign the reliability of all science. This maneuver avoids having to address the quality of justification for *particular* claims. Once again, general and specific levels are inappropriately conflated.

Stories of scientific change are a potential minefield for science educators. It was perhaps for this reason that historian Stephen Brush (1974) posed the question, "Should the history of science be rated 'X'?" (referring to the then-new film rating system). He recognized that scientists were susceptible to error and bias, and so might not make good role models or nurture trust in science. Ultimately, he concluded that such lessons would, in fact, be beneficial. They would humanize and contextualize science, and debunk overstated mythic heroes. Understanding the limits of science is certainly part of NOS, and students can be reassured by *real models*: scientists who had made notable achievements, despite missteps or not exhibiting every ideal (Allchin, 2020a). Science teachers may thus need to be explicit about errors and scientific change to provide a fully contextualized and balanced (and honest) view.

Still, it is easy for perspectives on scientific change to provoke gloomy despair. Even among professional philosophers. In response to Kuhn's and others' insights, some reasoned that since so many scientific theories in the past have failed, then current theories are inevitably doomed to fail, as well: the bleak outlook formally called the "Pessimist's Induction" (Laudan, 1981; Stanford, 2006). "How can we guarantee that our present knowledge is any better?", the skeptic asks. It hardly matters if science corrects some errors. There is no backstop for later reversals. Here, we see an echo of how the letter writers (above) reasoned. This nihilistic style of thinking about scientific change (beyond the notions of tentativeness, durability or self-correction) is another challenge for science educators.

What is arresting about most educational accounts of scientific change—embodied most notably in the "tentativeness" conception—is that they seem to assiduously avoid mention of error. There seems to be an implicit stigma attached to mistakes, even reasonable mistakes. This must change. Teachers need to articulate the concrete dynamics of scientific change, and not just rely on superficial abstractions or labels, or vague generalities. That includes discussing errors. And it includes, equally, discussing how scientists find and resolve errors. Students need concrete examples of the reasonableness of errors—and then how they were later revealed and corrected (through stumbles in ongoing research, new instruments, new collateral knowledge, new theoretical perspectives, or sheer happenstance).

Errors are blind spots. At first, the flaws in the justification have escaped notice (or were simply beyond our conceptual horizon). So, finding and identifying errors requires *work*: *epistemic* work. For example, when Oscillation Project with Emulsion-tRacking Apparatus (OPERA) announced their finding in 2011 of a faster-than-light neutrino, it was an international headline. A fundamental assumption of relativity theory seemed threatened. But was the claim trustworthy? Should one say simply that the science was "tentative, but durable"? The investigative team was well aware that, with the deeply anomalous finding, something in the experiment might be awry. "Something." That did not tell them what, if anything, was wrong. The whole team had to re-examine the experimental set-up, their assumptions and data analysis. They checked the energy level of the neutrinos, the alignment of the neutrino path, the role of the Earth's rotation in possibly distorting the distance measurements, the local adjustments to the GPS time signals, and so on. After 10 weeks, they traced the problem to a loose cable transmitting the time signal. At that point, they seemed to have isolated the error. But they still had to fix it and test it all again. That included investigating exactly how much a loose cable (loose in just that way) altered the time signal. Only when all that was done could they confidently declare an error (Cartlidge, 2012, Sirri, 2012; Strassler, 2012; Zichichi et al., 2012). Ten weeks. Not very durable, on that scale. But, of course, what mattered was not the duration, but the nature of the justification—and all the evidence and work behind it. That *scientific* work of encountering anomalies and then resolving them is what teachers need to teach, not some vague label of "tentativeness" and a blind promise of possible evidence-to-come in some unknown future.

Finding the source of error in the OPERA experiment was, paradoxically perhaps, a discovery of sorts. Albeit of a negative kind. But it still involved collecting new evidence and reconfiguring the old evidence. Just like a detective thriller: when the evidence changes, so does the verdict. Again, that is epistemic work, *scientific* work (not the mere passage of time).

But just as there is no universal or algorithmic "Scientific Method," there is no uniform error-correction method. There is no prescribed formula for self-correction. To justify any given claim, scientists need to be aware of and check all the possible sources of error, or error types (Allchin, 2001). Ruling out each possible source of error is, in fact, essential to building confidence in a scientific conclusion (Mayo, 1996; Suppe, 1998). Those are the concrete benchmarks by which to measure "tentativeness" versus "durability"—not just some ill-defined "test of time" or promise of "ultimate" self-correction. Indeed, you can find such assessments in the Intergovernmental Panel on Climate Change (IPCC) reports, explicitly designed to guide policy makers by indicating the scientists' confidence in the various conclusions about climate change. The gradations of justification already permeate scientific practice. These are the analytical tools that we need to teach K-12 students if we are to prepare them to assess scientific claims in the media or elsewhere.

That is, if the aim is for consumer-citizens to be able to assess the trustworthiness of scientific claims in public discourse, then they need to be able (as noted above) to *differentiate* the reliable from the unreliable. It is not enough for them to understand how science works *ideally*. They *also* need to understand how, on some occasions (such as the early COVID pandemic), *real* science falters and yields unreliable claims (Allchin, 2012b). We must not pretend that mistaken science (or scientific misinformation) does not exist. Rather, we must help students develop the competencies to cope with them. And we must focus attention on what matters: the depth of the evidence and the completeness of the justification, with respect to possible errors.

One may thus easily regard "tentativeness" as a weasel term. It tries to hint at error while dodging any negative connotations. If one wants to exert scientific authority, one refers to the claim as "durable": one should not doubt the science. But if the claim later turns out to be mistaken (as in the early COVID pandemic), then one can easily backpedal and admit (now, with the privilege of retrospect) that the original claim was only "tentative" after all. (The same switching gambit appears in appeals to the "eventual" self-correcting nature of science). Again, the hedging provides no guidance for measuring the credibility or reliability of a *specific* scientific claim—precisely where we rely most on NOS understanding to inform individual decision-making.

The solution to the specter of scientific change, then, is not to shy away from discussion of errors. One should acknowledge them, while also clarifying *how* scientists err *and how they address them*. The strategies for managing possible errors—both methodological (calibration, controls, blinding) and social (peer review, critical discourse, follow-up research)—are tools in science. They are also important reference points for public assessment of the relative reliability of any particular scientific claim. But they cannot be summed up in a single word. Trying to stuff all this understanding into the weaselly term "tentative" should cease. Educators need to be forthright about errors in science, their consequences, how scientists address error, and how they remedy it when they do. Fortunately, educators may now benefit from recent and emerging work on the philosophy of error (e.g., Allchin, 2026; Mayo, 1996; Tuboly & Karakas, forthcoming).

4 "Tentativeness" and Other Proxy Concepts

Based on a fuller understanding of the history, philosophy and sociology of science, one can see that the rhetoric of tentativeness as a characterization of scientific change is deeply problematic. So, what is the alternative? If constrained by short, easy labels, what should we say instead, to convey these important lessons?

That science is *provisional*? That it is *fallible*? No, these are both too strong (like "tentative") and too indefinite about specific claims (about COVID or climate change, say).

That science *exhibits varying degrees of confidence in the justification*? Quite true, but not short and easy. And, more importantly, not descriptive of error or profound conceptual change.

Science *accommodates new evidence*? Closer to the mark, perhaps. But similarly bulky and awkward, while failing to dispel the teleology of cumulative progress, or the dilemma of error.

Perhaps we might say that science is *adaptive, or adaptive to new evidence*? Here we have terminology that conveys several things simultaneously. First, it acknowledges that science changes, yes. But (second) it *also* underscores the process. It focuses on why and how. Science does not change for arbitrary reasons. It responds to new data or arguments. "Adaptation" implicitly suggests that scientific knowledge is shaped through natural selection, changing with the environment of data and observations. Third, science transforms at the social (population) level, not by the say-so of single individuals. Adaptation relies on consensus. Fourth, the change is *responsive*, not internally driven by an invisible hand of "progress." That is, science does not "self-correct." It *accommodates* new evidence, when (and if) it arises. It relies on encountering anomalies, new information and new perspectives—all by happenstance. Like organic evolution, the advance of science is *non-teleological*: local, contextualized, and contingent, *not* inevitable. Fifth, although science changes—sometimes unpredictably—it tends to respond to the environment of data at any given time. There may be reversals later (flightless birds, marine mammals), but selection tends toward an optimum in the present only: the best we can hope for or expect? In all these ways, the inherent evolutionary metaphor honors the philosophical tradition of evolutionary epistemology, which has interpreted science in such terms (e.g., Callebaut, 1993; Hull, 1988; Plotkin, 1994).

Problem solved? No, not really.

The problem is deeper than an inopportune term, to be remedied with new vocabulary. The problem is the very urge to consolidate the dynamics of scientific change, error, and error correction into a single word or concept. Moreover, students need to learn not just that science changes, but *why*, *how*, and *when*. To use that understanding, they do not need declarative philosophical content knowledge, but competencies in epistemic assessment.

This became poignantly clear to me when I encountered some educational research about NOS views among career scientists (at the graduate, junior and senior levels) (Ariyaratne & Akerson, 2024). The educators concluded that nearly half the scientists had a "naive" view simply because the respondents defended the scientific consensus on a well-studied issue or considered it unlikely to change in the foreseeable future. In making their (highly critical) judgments, the educators insisted on explicit expressions that science is unilaterally "tentative." They disregarded the scientists' many qualifications and discussion of context (all aligned with more sophisticated perspectives by philosophers of science, acknowledging various levels of justification and reliability). These educators did not seem interested in learning about the nature of science in an authentic setting, as might be revealed by the practitioners themselves (e.g., Wong & Hodson, 2009, 2010). Rather, "tentativeness" itself had become the end goal, rather than appreciating how scientists reason about the evidence in the short vs. long term. (If you did not admit the eventuality of error fully—according to the educators' rubric—then you did not understand NOS). The educators' simplified concept had eclipsed real science. This is the (somewhat embarrassing) nightmare of regarding strict adherence to a truncated concept as a benchmark for NOS understanding.

As noted, this one-dimensional interpretation of scientific change cannot guide how a citizen or consumer should assess scientific claims in personal decision-making or public policy discourse. All the indoctrinated student can say is that science, even textbook science, might be—or *will be?*—wrong at some unidentified point in the future, for some unidentified reason. So (the student may aptly wonder): why bother learning any science at all? No wonder that there is a crisis of trust in science. The doctrine of "tentativeness" helps nurture it.

We may trace this problem to the derivation of the typical educator's view. Scientific practice has become successively distorted through layers of interpretation and reinterpretation. Historians interpreted the scientists. Philosophers interpreted the historians. Educators interpreted the philosophers, and then went on to derive a truncated version for teaching students. Each step has experienced sharpening and leveling: accentuating some salient details while pruning (sometimes essential) complexities. Context is lost and the concept becomes successively more easily expressed and more easily remembered, and yet appears more general (Gilovich, 1991; Heath & Heath, 2007). As a result, "tentativeness" (in education) *does not* describe the nature of science directly. Rather, it is a *proxy* for "scientific change" (in philosophy). (That, in turn is a proxy generalization or idealized norm of the details documented by sociologists and historians). And now, it seems—as exemplified by the researchers above—the proxy trumps the original. The heuristic has become an absolute rule. The *proximal* target, ironically, short circuits the ultimate educational aim of understanding how science works. Accordingly, "tentativeness" is not an "approximation," but an exaggerated *caricature* that distorts NOS and obscures effectively understanding contemporary socioscientific issues—with no clue that something might be awry.

And what is true for "tentativeness" applies equally to other components of the so-called NOS consensus list. Subjective NOS, creative NOS, empirical NOS, sociocultural NOS (and others) are derivative proxies. At best, these should be regarded as crude indicators about the diverse dimensions of NOS understanding. The informed educator should notice that many significant aspects of NOS—relevant to citizens and consumers, as well as scientists themselves—fall between the cracks. For example, the "consensus" list excludes conflict of interest, ethics, funding, confirmation bias, publication bias, critical discourse, disagreement, error-correction practices, and more. All these appear variously in contemporary SSIs.

The challenge, then, is to conceive NOS education in a way that does not dwell on a prescribed list of highly derived, simplistic—and easily misinterpreted or misunderstood—principles: the "generalized" approach (promoted by, e.g., Kampourakis, 2016; McComas, 2020b). How does one learn about scientific change without some prescribed concept (such as "tentativeness" or an alternate) as a benchmark or guide?

One strategy is to flip the script. Do not target a list of piecemeal NOS principles and then find a way to illustrate each through separate anecdotes (McComas & Kampourakis, 2015, 2020). Rather, render science in a holistic way. Guide students in analyzing and extracting a deeper understanding of history through reflective analysis (e.g., Azevedo & Del-Corso, 2024; Allchin, 2013; Allchin et al., 2014; Berçot, 2024; Hagen et al., 1996; Howe & Rudge, 2005; Klassen, 2006; Ricci et al., 2017; Wong et al., 2008). Namely, transform *NOS* education into NOS-inquiry learning or NOS-problem-based learning. Historical or contemporary cases are occasions for posing *questions* about the construction of knowledge and how we establish its reliability. NOS is not presented as ready-made conclusions, to copy and repeat, like so many other lecture lessons. Rather, NOS is *problematized* (e.g., Allchin, 2013, 2017b, 2020b, 2024c; El-Hani et al., 2020). "How did scientists know this?" Students thereby build an understanding of NOS in a thoroughly constructivist manner: organically and fully contextualized. They are thereby prepared to apply their learning to contemporary cases and socioscientific issues. They reason (as most do) analogically or from exemplars (Creager et al., 2007; Kuhn, 1970).

So: the classroom strategy is to simply engage in a multi-dimensional story of science, *highlighting the problems of constructing reliable knowledge*: in our case, focusing on the challenges of new evidence, anomalies, disagreement, errors, and correcting errors (for example, lessons listed by Allchin, 2012b, Table 3). Of course, one cannot reproduce the entirety of science in the classroom. Some tailoring is needed to produce manageable fragments. So, one takes samples. Cross-sections. Episodes. Case studies. Teachers need to articulate the concrete dynamics of scientific change, complexities and all (not relying on simplistic abstractions). Most importantly, they need to compare the "before" and "after" of cases of scientific upheavals. That includes detailing (1) the reasonableness of the original conclusions, (2) the circumstances that led to the emergence of new evidence, and (3) the often-difficult efforts to reinterpret it all. We must clearly convey how science functions, including how errors occur and, equally, how (and when) errors are corrected. Afterwards, students will have the details to apply their knowledge in similar real-life contexts.

Removing "tentativeness" as a term *and* also as a target concept might be seen as dismantling much-needed NOS education. But properly viewed, it is (ironically) a way to help students engage with NOS more directly, by placing them "inside" cases of scientific practice, like their counterparts in history and philosophy decades ago (on a different academic level).

5 The Challenge of Scientific Change and Public Engagement with Scientific Claims

As epitomized in the Pessimist's Induction and the Galileo Gambit (above), NOS thinking by citizens and consumers in today's culture can be treacherous. Based on "tentativeness" and allied general concepts, they can easily discount *all* science as unreliable. We need to focus instead on how scientists justify particular claims, and the role of the consensus of the relevant experts. We need to abandon the confusing language of "tentativeness" and "durability," and vague promissory notes about "eventual" self-correction. We need, rather, to engage students in understanding error, error types, the social practices of science (including critical discourse), the tools for ensuring and assessing reliability, and the scientists' own views of their unresolved uncertainties. These are the tools of the citizen-consumer for addressing SSI-related claims. Not truncated NOS content (especially reduced to one-word sound bites), but NOS practices.

First, we need to be forthright about error. For example, we can transform the case of the early COVID pandemic (introduced in the opening of this paper) from a potential circus of science denialism into a prime learning opportunity about NOS. (And not merely for indoctrinating students by preaching a prescribed list of general NOS principles). We can motivate and lead inquiry on the reliability of various reported scientific claims. And when students encounter instances of scientific change, the teacher facilitates active NOS-centered problem-solving.

The strategy (as described above) is: first, problematize NOS. What were the scientific claims, why were they endorsed (or, possibly, espoused without any genuine scientific research), and how did they all fare in the long run? If there were errors, why? How were they found and resolved? What do such cases tell us about avoiding similar errors in the future? The enterprising teacher can easily find online a catalog of errors during this episode (or they can invite students to take on that responsibility). Some examples might include:

(1) The COVID virus is transmitted by contact.
(2) Health care workers, but not the public, should wear masks.
(3) Herd immunity will help limit the spread of the disease.
(4) Vaccines (once developed) should be fully effective.
(5) COVID (like the flu) is an acute illness, with no long-term effects.
(6) Despite mutations, the basics of the disease and its transmission should remain consistent.
(7) Mutation rate should be low, like similar viruses.
(8) Expect the risk of illness to be evenly distributed across the population.
(9) A vaccine cannot be developed any faster than 12–18 months.

Of course, these must be coupled (and perhaps mixed blindly) with controversial claims that scientists generally got *right*. For example:

(10) Epidemiologists had expected such a global pandemic for a long time (on the scale of the 1918 "Spanish flu" pandemic).
(11) Hydroxychloroquine is unproven and likely ineffective at preventing or treating COVID.
(12) Asymptomatic patients might still transmit the virus.
(13) Although it has been just two months since travel screening began, and we have seen only ~ 100 COVID deaths to date, we can expect 2 million people to die in the U.S. in the next few years.
(14) While the incidence of COVID is waning now (late April, 2020), we can expect a second, larger wave in the fall.
(15) New mRNA technology shows strong promise for developing a vaccine.

To these, one might elect to add several claims reported in the media, whose "scientific" status was perhaps open to debate (Allchin, 2020a, 2024a):

(16) Elderberry tincture, anti-viral aromatherapy, oregano oil, colloidal VitalSilver, boneset tea, and frankincense are all recommended remedies.
(17) On March 24, Nobel Prize winner Michael Levitt declared a peak in cases and predicted a permanent decline of cases in Italy, the U.S., and elsewhere
(18) On January 22, 2020, a Belgian doctor attributed the cause of the COVID pandemic in China to radiation from 5G cell phone towers, and many celebrities echoed his warnings.
(19) On April 24, 2020, the President of the United States suggested drinking bleach as a disinfectant.
(20) In mid-May, 2020, many news outlets called the virus a hoax, intended to influence the Presidential election.

Here, then, is healthy sample of scientific claims for NOS investigation and learning (possibly one for each student or student pair?). Again, most of the information to assess these claims in a historical perspective is available online. (And who cares on this occasion if students rely on AI to generate an answer, so long as the sources are cited accurately—including the AI program itself?) (1) How did each claim about COVID originate and where was it reported? (2) What was the evidence and/or the argument, presented with what confidence? (3) What was the ultimate fate of each claim, after how much further research or investigation? (4) How did the evidence change, and how did that alter the conclusion? (5) What general lessons should we learn, as scientists or as consumer-citizens, about interpreting the reliability of scientific claims in public discourse?

This activity supports several aims. First, it indicates that science, especially in the early stages of research, arrives at claims that vary substantially in the reliability of their justification. Second, it helps students understand *why* the reliability of those claims varied. It helps identify various *sources of error* in science, and acknowledges (honestly) that, yes, errors can occur. But at the same time, it *also* shows how scientists discovered that those initial claims were wrong, and *how* they reached more secure conclusions, typically based on more (deeper) evidence. This addresses the problem of informing student not just *that* science changes, but also *why*. Third, by identifying various sources of error, it helps students learn the appropriate questions to ask to differentiate (a) well-tested claims, (b) qualified (or limited) claims, and (c) uncertain (truly "tentative") claims. Fourth, it helps students differentiate misinformation from honest error and natural scientific change. Some purported "scientific" claims are wrong, not because the scientists made any misstep, but because someone in the media irresponsibly called their claim scientific. Fifth, students may begin to appreciate what sources of scientific information (from scientific institutions and reliable news media or science journalists) tend to be most reliable in the long run. In summary, a lot of lessons for one short, easy activity. Indeed, I contend that this activity can teach students more about the nature of authentic (not idealized) science (and perhaps science media literacy) than many black-box NOS activities or powerpoint presentation on tentativeness—and (importantly, from the teacher's classroom perspective) with no greater effort or investment of time.

The internet and social media have transformed the landscape of science education (e.g., Höttecke & Allchin, 2020; Osborne et al., 2022). Even with the ready availability of information on just about everything, all with a few keystrokes, we cannot expect students to become expert on every socioscientific issue or to assess all the evidence themselves.

Information alone does not yield *knowledge* or *understanding*. The one-time vision of intellectual independence can no longer be sustained as realistic (Norris, 1995, 1997). We must help students, instead, learn how to navigate in a world full of distributed expertise and specialized knowledge, polluted by rampant scientific misinformation (Allchin, 2022). They need to learn how to differentiate reliable from unreliable scientific claims, all without being an expert themselves. That inevitably involves understanding how such knowledge is produced and how it is communicated, from test tubes to YouTube, from lab book to Facebook (Allchin, 2013). As I hope to have conveyed here, that involves more than just a casual acquaintance with a handful of simple NOS statements, such as "science is tentative." It entails Whole Science (Allchin, 2012a, 2013; 2017a; Allchin & Zemplén, 2020): a broad familiarity with scientific practices and how scientists manage error, and with what consequences and limits. And that includes the *social* practices of science—critical discourse and resolving disagreement—that yield a trustworthy consensus. That is, science students need to appreciate the social architecture of scientific knowledge that allows them to find—and trust in—credible scientific information, ultimately based on nature-of-science inquiry.

Notes

1. Mueller and Reiners (in this journal, 2023) construed Popperian falsification as the conceptual basis for "tentativeness." This view is mistaken, both philosophically and historically. Popper's notion was an idealization, that fit neatly with a view of science as structured by strict logic and universal laws. Following Kuhn's historical turn, philosophers widely acknowledged that reasoning in real science is far more complex and nuanced. Philosophers now reject falsification as a legitimate model (e.g., Donovan et al., 1988; Engelhardt & Caplan, 1987; Losee, 2005), although it lingers more modestly in inspiring the strategy of severe tests e.g., (Mayo, 1996).
2. "Self-correction" is distinct from *accommodation* (Allchin, forthcoming). McComas (representing a widespread posture) comments that science is "subject to revision when additional information is presented" (2020b, p. 59). This is a critical stipulation. The important first step in correction is finding or encountering the relevant new evidence. Namely, the essential "additional information" arises contingently. It is never guaranteed. Hence, science is not "*self*-correcting" in the sense of systematically detecting and eliminating error. For example, in the case of monarch/viceroy mimicry correction appeared only after decades.

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