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SCIENCE STUDIES AND SCIENCE EDUCATION

Teaching the Nature of Science through Scientific Errors

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ABSTRACT: Error in science is a prime occasion to teach the nature of science, especially the central feature of tentativeness. Error types also reflect corresponding methodologies of science, critical for practicing science and (in a context of scientific literacy) analyzing its claims. Effective efforts in teaching about error will ideally be informed by earlier educational perspectives and a schema for inventorying and organizing error types. Approaches using student-directed inquiry have limits, whereas guided-inquiry historical case studies seem appropriate vehicles. On a larger scale, one may also envision a prospective learning progression on successively deeper understandings of error in science. Sample case studies and opportunities for further reading are identified. © 2012 Wiley Periodicals, Inc. *Sci Ed* **96:**904–926, 2012

ERROR AND THE NATURE OF SCIENCE

If the goal is to teach "how science works" (Board of Science Education, 2011; OECD, 2009), then it seems equally important to teach, on some occasions, how science *does not* work. Imagine teaching law and law enforcement without crime. Or medicine without disease. One needs to understand how health can fail or how laws can be broken if one is to understand how the relevant systems function properly. Biologists and engineers are already familiar with cases of loss of function as a strategy for research and for teaching structure and function (Bechtel & Richardson, 1993, Petroski, 1994, 2006). So, too, for the nature of science (NOS). Every erroneous conclusion in science is a potential occasion for learning "scientific practices," or how scientists build reliable claims.

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For over half a century, one feature has remained central in virtually every recommendation to teach NOS: that science is "tentative" (HIPST, 2008; Lederman, Wade, & Bell, 1998). The label varies. Some say that science is fallible, provisional, or contingent. Others say it is developmental, changeable, or subject to revision—but with a sense that new concepts replace old ones, not merely that knowledge grows or progresses cumulatively (Kuhn, 1970). Ultimately, scientists can err. Scientific claims can later prove to be mistaken. Mere classroom allusions to possible failure, however, cannot dislodge the potent cultural image of science as an amalgam of fact, certainty, and incontrovertible evidence. Just mentioning that "science is tentative" seems to function culturally like an escape clause, excusing science any time it does not meet the ideal. The ideal will persist. Indeed, that naive view has prompted ill informed lawsuits against scientists for their published mistakes or, in a recent case, their failure to predict an earthquake (Hall, 2011; Steinbach, 1998)! If students are ever to learn that science is "tentative," they must encounter real, concrete examples of scientific error or failure. One may surely couple them with examples of scientific change or the remedy of error, to show how knowledge grows. But the fundamental challenge is to teach fully about cases of error in science.

But more than this, students also need to learn *how* science can go wrong. Many persons appeal to the tentativeness of science to justify their rejection of evolution, climate science, or vaccines (Allchin, 2011a, 2012b). They do not yet appreciate the need to identify *particular* possible errors. The scientifically literate individual needs to be able to interpret, say, revisions in the recommended ages for mammograms or the retraction of a study linking a virus to chronic fatigue syndrome. Here, mere awareness of tentativeness is inadequate. They need to know why and how the science can change, or how initial errors can be remedied. They need to know how to probe the epistemic structure of scientific claims, to discern reliable ones from suspect ones. That is, they need to know the many sources of error, or the ways an individual claim or its evidence may be vulnerable. From engagement with historical cases, then, they must also become familiar with the spectrum of *error types* in science (see Table 2 and discussion below). Understanding scientific error types is an analytical tool essential for scientific literacy.

At the same time, knowledge of error types contributes to understanding effective scientific methods. Philosophers and sociologists of science have long appreciated that methodological norms complement particular error types (Table 1). Most methods in science were not obvious at first. They have a history. Scientists learned them through reflection and often after a repeated pattern of error. Even the basic notion of experimental control has a history. The earliest examples of control, one finds, nearly always introduced a second experiment mindful of potential criticism or ensuring that a target cause was not mistaken. Only in the mid-to-late nineteenth century does one find the method articulated and the term "control" introduced (Oxford English Dictionary, 1971, I, p. 927). That is, the methods of science are the hard-won wisdom of experience with error. Similarly, students must learn the role of each method. History can be a teacher's roadmap—perhaps guiding lessons without any of the negative consequences of personal failure. Namely, as exhibited historically, error is a potent vehicle for learning about the methods that ensure reliability in science. Every error helps profile (by contrast) an element of how science works (more below).

Although scientists may succumb to errors, as in any human endeavor, they surely aim to prevent, mitigate, or accommodate errors. Ideally, researchers actively review their work for possible errors. This posture of critical questioning is often described as a skeptical attitude and hailed as a hallmark of science. Yet skepticism can easily become aimless disbelief. Vague skepticism differs significantly from a focused search targeting *particular* sources of error, or error types. Teachers should thus avoid the rhetoric of skepticism and teach instead the role of concrete error analysis.

TABLE 1
Errors in Science and Their Corresponding Methods Derived Through Historical Experience

Error	Method	References on History
Placebo effect	Blind clinical trial	Herr (2011) Kaptchuk (1998)
Observer effect	Double-blind	Shapiro and Shapiro (1997)
Coincident variables	Controlled experiment	Boring (1954) Lilienfeld (1982)
Sampling error	Statistical analysis	Hacking (1990) Porter (1986)
Biased sampling	Randomization	Hall (2007)
Instrument malfunction	Calibration	Franklin (1997)
Inappropriate inferences from results and use of methods	Peer review	Benos et al. (2007)
Gender or cultural bias	Communal checks and balances	Harding (1991) Longino (1990) Solomon (2001)

For all these reasons, then, scientific error would seem to have a major role in NOS education: to convey the “tentativeness” of science, to clarify the meaning of a “skeptical attitude,” to teach the roles of proper methodologies in establishing reliable claims, and to help equip individuals for analyzing the epistemic structure of scientific claims in personal and public decision making. Teaching NOS tends to be very general, as expressed in the familiar NOS consensus list (McComas & Olson, 1998; Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003). A focus on error makes this particular, hence applicable to, concrete cases of everyday scientific literacy (Allchin, 2012b).

How, then, might educators meet the challenge of teaching about scientific error? First, they may explore earlier educational, philosophical, historical, and sociological perspectives for guidance (the following section and the Appendix). Second, using such background, they will clarify the nature and scope of the task by conceptualizing or characterizing error (see Table 2 below) and what is central to K-12 learning in a context of basic scientific literacy. Third, they will consider appropriate approaches or strategies (ensuing section) and the resources and curriculum materials that are already available to apply them (see Table 3 below). Finally, they may reflect on a larger scale about organizing multiple lessons across many years, through prospective learning progressions (final full section).

SCIENTIFIC ERROR IN SCIENCE EDUCATION AND SCIENCE STUDIES: A RICH HERITAGE

Notions about portraying scientific error in science education are not new. They extend back over half a century. For example, Leonard Nash (1951), cofounder and coeditor of the *Harvard Case Histories in Experimental Science*, commented on why one might use history, linking it to profiling error and NOS. He was concerned about the misconstrual of experimental data, whether it was the historical case of weight gain of calcined metals or a contemporary case of the radioactive dating of meteorites. He also cited Dalton’s prejudices in the development of atomic theory:

> Dalton's theory was derived by a wild and almost completely erroneous line of argument based on physical phenomena that were largely irrelevant to a chemical atomic theory. (p. 151)

Rejection of Avogadro's hypothesis was among Dalton's (and others') errors. Thus, Nash advised a role for history:

> We believe that in calling attention to the difficulties, delays, and failures of science, as well as to its triumphs, we present a truer, better-rounded, and much more useful picture of it as it was in the beginning and as it is today. (p. 151)

Nash felt that the informed citizen needed to understand how scientists could err.

High school chemistry teacher Herb Bassow (1991) also noted the significance of conveying the importance of errors in science. He illustrated this with a case from the 1920s where a graduate student, E. Bächlin, encountered problems measuring the wavelength of X-rays. His research led him through a thicket of prior error: from Millikan publishing an incorrect value of the charge of the electron (having used an incorrect value for the viscosity of air in the Stokes equation) through calculations of Avogadro's number (based on Millikan's e) to calculations of atomic distances in salt crystals (based on N) and calculations of the X-ray wavelength based on the X-ray crystallography of NaCl (using a now erroneous d in Bragg's equation). Errors by five Nobel Prize winners, in all. How better to convey the interdependency of science?, Bassow argued.

Earlier I, too, profiled "the virtues of teaching the wrong ideas from history" (Allchin, 1995). History helps us understand, first, how "wrong" ideas could once be considered "right." It also shows how such views changed. History thus shows how science can err *and* how it can remedy those errors. Addressing historical errors contributes to understanding the limits of scientific justification. Philosopher of science John Losee (2005) followed this approach in profiling "theories on the scrap heap," namely, why scientists abandoned theories they once held as true. Learning how science could once reach conclusions now deemed unreliable is critical for understanding episodes of conceptual change today.

Ironically, we may not wish to banish astrology, alchemy, phrenology, craniology, mesmerism, or other pseudoscience from the science classroom (Allchin, 1995). Historically, each of these practices was once considered science—in some cases, exemplary science. Students are no different. They need to work through such examples to understand what makes modern science "science." History of pseudoscience offers an ideal occasion for doing so (Duncan, 2000). Every generation must relearn what is scientific, what pseudoscientific (Allchin, 2004a, pp. 189–191). As noted by Wandersee (1986), historical error may also be important for understanding student misconceptions and identifying what may lead them to deeper understanding. Historical errors may also be fruitful vehicles for teaching content effectively.

Mermelstein and Young (1995) also profiled a role for error in the process of science and learning. They emphasized that individual "mistakes are vehicles for discovery," both among scientists and students. They followed, in particular, the lead of William Beveridge in *The Art of Scientific Investigation* (1957):

> Perhaps the most striking examples of empirical discoveries are to be found in chemotherapy where nearly all the great discoveries have been made by following a false hypothesis or a so called chance observation. (p. 43)

That is, student errors are ideally treated as "springboards for inquiry" (p. 773). This psychological process at the individual level is then integrated with the reduction of error at the level of the collective, or scientific community. Scientific knowledge grows by trial and error, of course, but not blindly. Science—and science education—needs appropriate management of those errors, especially at the social level.

Guinta (2001), who manages a Web site for historical papers in chemistry, has also turned to the role of errors in "using history of chemistry to teach scientific method." Errors, he notes, help mitigate two major pitfalls in historical lessons: hero worship, along with its "unwarranted impression of infallibility," and impressions of scientific method as algorithmic, rather than guided by "judgment and imagination" (p. 623).

> Acknowledging the false steps of great scientists avoids putting those scientists on a pedestal and illustrates that there is no automatic or mechanical scientific method. (p. 626)

Guinta, too, finds error essential in rendering the persistent NOS theme of tentativeness. He provided several historical examples in chemistry. Errors are thus valuable for counteracting the distortions of scientific "myth-conceptions," the idealized and monumentalized images of science typically found in the media and textbooks (Allchin, 2003a). Cases of reasonable error or fallibility, especially among scientific heroes, function as NOS discrepant events or NOS anomalies that trigger reflection and deepen understanding of NOS (see papers by Darden and Allchin in the Appendix). Sometimes following the "right" methods can lead, paradoxically, to the "wrong" conclusion.

Given that idealized science and heroic scientists are not perfect, we need to differentiate between role models and *real* models (Allchin, 2008, p. 504). The former may be so idealized that students view them as unattainable: that is, as *negative* role models. The latter are more human in scale and more accessible to a wider variety of students, especially women and minorities. Portraying error in science reveals its human dimension and may thus help motivate students and, counterintuitively perhaps, foster recruitment into scientific careers.

One particularly prominent error in science and elsewhere is confirmation bias (Nickerson, 1998). That is: "information that is consistent with our pre-existing beliefs is often accepted at face value, whereas evidence that contradicts them is critically scrutinized and discounted" (Gilovich, 1991, p. 50). Earlier I noted the need to profile this cognitive tendency in science (as well as in ideas *about* science) and to foster practical skills in cognitive checks and balances (Allchin, 2003b). One solution to this problem is a variant of Karl Popper's severe tests:

> It is not enough, for example, merely to advance a hypothesis, deduce some of its implications, and then confirm them through testing. The hypothetico-deductive method leaves too much open to error. One must pursue *severe* tests. [Deborah] Mayo thus adds an important principle for regulating error: *error probes* ([1996] pp. 64, 445). That is, to deepen reliability, one must actively and aggressively search for possible mistakes. (Allchin, 2003b, p. 325)

Confirmation alone can be epistemically treacherous, blinding one to alternatives. An awareness of errors due to confirmation bias can highlight importantly how the canonical "scientific method"—simple hypothetico-deductive thinking, without consideration of alternatives or sources of error—is deeply susceptible to such bias.

Recently, Kipnis (2011) claimed that "so far, incorporating the subject of error into science education apparently has been limited to errors of measurement . . . and ethical issues. . . " (p. 656).[1] By contrast, as noted above, there has been a rich heritage of ideas

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[1] For example, Zachos, Pruzek, and Hick (2003) also opened a "place for the issue of scientific error in the secondary science curriculum" (p. 947). They framed a vast scope for error—for example, drawing on Bacon's characterization of the many "idols," or psychological sources of bias in reasoning—yet remained focused rather narrowly on experimental errors in measurement, drawing on the conventional distinction between measurement uncertainty (a form of randomness misleadingly called "error") and systematic bias.

about addressing error. They seem to affirm the significance of teaching about scientific error, while highlighting the role of historical examples, as well as student inquiry, as specific approaches. My analysis here extends these perspectives by claiming that understanding *error types* is an effective way to learn about the conventional scientific methods and by envisioning such lessons in a learning progression. Errors provide a window into how science works.

Having established an educational goal, the educator might next turn to looking for further background and insight on error in science. Informal browsing will certainly identify a handful of popular volumes: Nichols (1984), Kohn (1988), Youngson (1998), Gratzer (2000), and Grant (2006). (Add, too, one rather delightful children's book: Kelly & Parker, 1996.) Yet, as one might well expect with their popular audience, they largely entertain more than inform. They generally portray error in science as a blend of embarrassment and bemusement, as reflected in their titles: *Scientific Blunders, Shocking Science, False Prophets, The Undergrowth of Science*, and *Discarded Science*. These volumes do not engage with error as a normal feature of science. For example, they do not even reflect the consensus in current NOS educational literature and policy documents for acknowledging science as tentative. Still, for educators, they can help exhibit common preconceptions (and misconceptions) and affective attitudes about error. Namely, error is often seen as a diversion, in both senses: It diverts us from the "true" course of science and distracts us pleasantly by amusing us. In this view, scientists are easily faulted (or ridiculed) for their lapses. This is the naive view that educators must (in a constructivist framework) engage and address.

Scholarly treatments of error are sometimes no better. Many authors (typically veteran scientists) seem to revel in portraying error in science as *pathological* (Dolby, 1996; Langmuir, 1989; Rousseau, 1992; Turro, 1999; also Pigliucci, 2010). However, their accounts are typically privileged by retrospect. They betray efforts to bolster the pristine image of scientific authority. By disregarding historical context, they oversimplify and idealize science (Allchin, 2003a; Butterfield, 1959; Chang, 2009). Through anachronistic judgments, they eclipse the inherent uncertainty of science at any given moment, misportraying a key feature of NOS. Error in science is seldom about delusion, self-deception, or human frailty, as they suggest (Bauer, 2002). That posture reflects a poor appreciation of error types, the sources of error, and the history of scientific error. Again, this is a potent glimpse of the challenge that teachers face.

Still, historians, philosophers, and sociologists of science, cognitive psychologists, and others in science studies have written informatively (if not extensively) on error in science. For convenience, I have surveyed some of the most informative sources in a separate bibliographic essay, found in the Appendix. All these sources may—and perhaps should—inform an approach to teaching about error in science. They can alert educators to NOS preconceptions, profile the scope of scientific errors and scientists' strategies for addressing them, highlight cognitive limitations, and provide numerous concrete cases for classroom study and analysis.

CONCEPTUALIZING ERROR IN THE CLASSROOM: DEVELOPING A STRUCTURED INVENTORY OF ERROR TYPES

Again, scientific error is significant in education for profiling and rendering, through its inversion, how science works, or NOS (both as product and process). Indeed, a clearer understanding of the many sources of error may help educators conceptualize NOS itself more clearly. How should one structure such an understanding?

One might imagine that to conceptualize error, one must begin with a definition—a common impulse.[2] Yet one can certainly pursue science without a formal definition. Cultures were investigating nature and differentiating between effective trials and error, and between reliable and unreliable conclusions, long before there was a formal concept of science (or philosophy of science). Definitions emerge only late in the process. In practice, the rejections of Ptolemaic astronomy, catastrophic worldwide floods, and polywater did not hinge on any subtle definition of error.

Error is, ironically, notoriously difficult to *define* unambiguously. One reason is that the concept of error is typically diachronic. If one knew that one was making an error, it would not be an error. Such judgments are made in retrospect (or from an “informed” perspective, with respect to another, “ill-informed” perspective). In clumsy hands, a definition of error merely reduces to regarding the perspective of the speaker at hand as legitimate: *I* am right and *you* (*they*) are wrong. Another common tendency is to refer to the ultimate truth or falsity of a claim—trying to transcend the very epistemological problem that error presents. With no independent access to reality, however, all knowledge claims must negotiate the challenges of evidence, demonstration, and persuasion through such strategies as intervention or robustness of data (Hacking, 1984; Wimsatt, 2007, Chap. 4). An error claim is ultimately a form of *negative* knowledge. It requires evidence. An error—once ascertained—is, paradoxically, a new fact (Allchin, 1999).

In investigative practice, awareness of an error typically precedes any clear articulation of what precisely the error is. Errors first “appear” as a *discordance* of different experimental results, an *inconsistency* among concepts, an *anomaly* between observations and theoretical expectations, or a *disagreement* on any of these among different researchers (Darden, 1991; Franklin, 2002; Kuhn, 1970). The next step is to “isolate” or identify the error (Bechtel & Richardson, 1993; Darden, 1991). Once the error is confidently articulated, one has, ironically perhaps, *discovered* something new. One has *learned* more deeply how to interpret the evidence—and *also* how one can misinterpret the evidence without complete knowledge. That new conception, at a finer level of resolution, replaces the former one. Thinking about error fully and in detail can be puzzling indeed.

One could also focus on what counts as a *scientific* error (e.g., Kipnis, 2011, pp. 657–659). This is akin to trying to demarcate science (or do the “boundary work” profiled by Gieryn, 1999). Fraud, for example, is often characterized as external to science *proper*, even though it is perpetrated by scientists, is found in the scientific literature, and can affect day-to-day research activities. Fraud is simply an error in the social system of trust and credibility (Allchin, 2012a; Shapin, 1996). The error is not the original lie, but the mistaken belief in the lie, along with the implicit trust that ultimately proves unwarranted. Misconduct is different from error. Misconduct is a disvalued behavior, based on a *moral* judgment. An error is an unreliable claim, based on an *epistemic* assessment. It is all too easy, of course, to define science *normatively* rather than *descriptively*. One can try to stipulate that science *is* what scientists ideally *ought* to do. That fits a *political* goal of safeguarding scientific authority. However, the ideal does not always match how scientists reach reliable conclusions *in practice*. An idealized approach inevitably leads to a view that science is error free and that all scientific error is pathological (see above). While one can adopt this posture, it is does not contribute to solving the challenge of interpreting how errors emerge and with what consequences. When scientific conclusions go awry, including in public settings, it is important to understand why, whether one labels it “scientific” or not.

Another tendency is to associate error with blame or accountability (whether political or moral). Error is viewed in terms of the *scientist*, rather than the scientific knowledge. Error is

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[2] For example, Kipnis (2011) and one reviewer of this paper.

conceived as a violation of implicit scientific norms and is equated with misconduct (Kipnis, 2011; Kohn, 1988). This often leads to harsh personal judgments of "impeding" scientific progress (Langmuir, 1989). But many scientific norms are not absolute. They are heuristics, or guides to epistemic productivity, not inviolable rules (Wimsatt, 2007). Ultimately, what matters is the reliability of the conclusions, not some imagined method that might guarantee such conclusions. A judgment of *fault* or *responsibility* is independent of (and typically based on) a prior assessment of the *evidence* for a scientific claim. Scientific error relevant to scientific literacy and education is about *scientific claims,* not about *scientists*. That perspective is also important pedagogically when addressing a student who has made a "mistake" in their own lab work.

What matters for teaching NOS, ultimately, is how scientific claims can fail. One needs, more than any formal or abstract definition, an awareness of the various *error types*. A science teacher needs an *inventory* of possible sources of error, an appreciation of their *variety,* and some scheme to *organize* them. Or course, sources of error parallel methods for avoiding them and for ensuring reliable claims. A scheme of errors is also, indirectly, a scheme for validating scientific knowledge (Allchin, 2001; 2011a, Table 3).

In interpreting error, it is fruitful to conceptualize scientific theories as selective representations, models, or *maps* (Giere, 1998, 2006; Turnbull, 1989; van Frassen, 1980; Ziman, 1978). That is, a theory, concept or other claim is a "mapping" of some aspect of the physical world.[3] In the widely used map metaphor, the phenomena are the territory. Scientists develop maps and then maps *of* maps in successive layers. A scientific claim is ultimately a multilayered mapping of converging chains of reasoning from data. All may be traced to a collection of initial observational benchmarks (including measurements and other data collection). But every step in the chain of mapping must be secure to deem the claim reliable. Each transformation or synthesis, traced all the way back to the original observations, requires justification (Hacking, 1984). Each is also subject to error. Thus, every error (conceived as an error type) in turn reveals a piece of the general structure of the reliability of scientific claims. Again, the potential for error and the process of justification mirror one another. A student learning about error is, ideally, simultaneously also learning about epistemics.

The image of successive layers of mapping provides a simple organization for conceptualizing the emergence of scientific knowledge: from local data to global theories, from laboratory data to policy claims in cultural context, from test tubes to You Tube, and from the lab bench to the judicial bench. This structure helps to organize error types—and the corresponding features of effective scientific practice that they indicate—into a general view of the scientific process and its justification (Table 2): a hybrid of sorts between an idealized procedural scientific method (or inquiry process) and the structure of the final scientific argument (Deng, Chen, Tsai, & Chai, 2011). An inventory of error types helps in recognizing and filling in the mapping structure. Where along the series of transformations from data to claim does each error type occur? What feature of scientific practice or reasoning failed and needs instead to be ensured? Ultimately, it is the spectrum of error types and their organization, not definitions, that is important in thinking about and analyzing error in public settings and hence in the science classroom.

This structure allows one to organize and situate the variety of errors encountered in the classroom (through student inquiry or guided case study) and in authentic social settings beyond school. Errors may further be classified in broad categories. At the most general

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[3] See Hacking (1984, pp. 208–209) on the complex transformations that yield microscope images and Latour (1987, pp. 195–257) on the transmission of claims extended through social networks.

TABLE 2
Taxonomy of Error Types

LOCAL

Material
- Improper materials (impure sample, contaminated culture)
- Improper procedure (experimental protocol violated, poor technical skill)
- Perturbation of phenomenon by observer (placebo effect)
- Failure to differentiate similar phenomenon through controlled conditions

Observational
- Insufficient controls to establish domain of data or observations
- Incomplete theory of observation (instrument/protocol not understood)
- Observer perceptual bias (“theory-laden” observation, need for double-blind)
- Sampling error (statistical rarity, weak significance level cutoff or other probabilistic factors)

Conceptual
- Flaw in reasoning (includes simple computational error, logical fallacies, mistaking correlation for causation, incomplete evidence)
- Inappropriate statistical model
- Inappropriate specification of model from theory
- Misspecified assumptions or boundary conditions
- Theoretical scope (domain) over/undergeneralized
- Incomplete theory, lack of alternative explanations (limited creativity)
- Cognitive biases (misplaced salience, normalizing)
- Theory-based cognitive bias, entrenchment
- Unchecked sociocultural biases (gender, ethnicity, economic class, etc.)

Discursive
- Communication failures: incomplete reporting, obscure publication, translation hurdles, patchy citation/search system
- Mistaken credibility judgments (Matthew effect, halo effect)/ fraud
- Breakdown of systems for credentialing scientific expertise
- Public misconception of scientific results and misunderstanding of science (poor science education, poor science journalism, etc.)

DERIVED (GLOBAL)

level, error types or possible sources of error may be sorted into experimental (material and observational), conceptual, and social (see Table 2),[4] as illustrated below.

For example, several years ago, the media reported studies implicating a virus in chronic fatigue syndrome. Now it appears, through additional research, that the clinical samples and reagents in that original study were contaminated (Simmons et al., 2011). The initial conclusion was compromised due to a simple material error. Admonitions to students to take samples carefully or wash glassware fully are not just preoccupations of fussy teachers.

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[4] See Allchin (2001) for fuller discussion and Hon (1989) for a similar framework oriented more narrowly to experimental practice.

They embody important NOS lessons about an error type, although the lesson may not seem significant to a student until confronting a case such as this.

Observational error types, such as inadequate sample size, can also have major socioscientific consequences. In 2008, the drug Avastin was approved by the U.S. Food and Drug Administration (FDA) for use in treating breast cancer, based on preliminary studies, which showed a statistically significant benefit. After further studies among a larger body of patients, however, this apparent benefit disappeared (FDA, 2011). The initial study was not methodologically flawed, but its conclusion nonetheless now seems in error. Sample size matters. This lesson is often targeted in conventional classroom labs. But it seems difficult to thereby impress upon students the ultimate lesson. Erroneous results make it abundantly clear.

Even if experimental results or field studies seem correct, error may still emerge in subsequent levels of interpreting data. In his 1985 *Sociobiology*, E. O. Wilson presented a genetic explanation for social structure in ants and other insects. The dramatic account fueled beliefs that human behavior, too, was directly linked to genes. Wilson's provocative book, *On Human Nature*, won a Pulitzer Prize. Research boomed. *Time* magazine boldly reported on its August 15, 1994 cover, "Infidelity: It may be in our genes." A genetic explanation for cooperation is now stock content in introductory biology textbooks (Allchin, 2009b). Not long ago, however, Wilson essentially recanted (Nowak, Tarnita, & Wilson, 2010). The causation interpreted from the observed correlation now seems to be in the reverse direction: from social structure to reproductive genetics. Strong theoretical biases may have shaped what now seems a significant error, including among those who accepted the theory. The error certainly had substantial consequences for social ideology, based on beliefs in biological determinism (Lewontin, Rose, & Kamin, 1984). Interpreting ideas like these certainly seems to exemplify the widely proclaimed educational goal of scientific literacy. Interpreting the error seems equally important, along with the corresponding cautionary lesson about science that seems to naturalize cultural beliefs. Soon, science teachers may be needing to explain to students why their textbook is wrong. That will be an occasion for a vivid NOS lesson about reasoning in theoretical and cultural contexts, based on a concrete conceptual error.

Finally, one may consider discursive error types, in the realm of communication, science journalism, and public understanding of science. In December 2010, the media were abuzz with reports of bacteria incorporating arsenic in lieu of phosphorus into their DNA. The *New York Times* reported prominently on its front page, "Scientists said the results, if confirmed, would expand the notion of what life could be and where it could be" (Overbye, 2010a). The buzz was short-lived. Criticism emerged, and the results and validity of the methods were questioned (Overbye, 2010b). The reported claims quickly dissolved. In this case, NASA had promoted the paper before its publication and before peer analysis had been given an opportunity to work. The announcement of findings "that will impact the search for evidence of extraterrestrial life" was premature, much like the now infamous 1989 claims about cold fusion. The substantive error here was not so much in the study itself, as in short-circuiting the social process of scientific review and criticism. Another cautionary tale for students as consumers of science in the news and an occasion to appreciate the corresponding role of critical discourse.

The four errors above each represent an error type that recurs and that helps, indirectly, characterize effective scientific practice, or how science works (when it does). As an ensemble, they help delineate the structure of successive inferences that originate in observations and measurements and end possibly on the front page of major newspapers: from calibrating an instrument to taking measurements, to calculating differences between experimental and control group, to assembling values in a graph, to comparing the curve with another graph, to analyzing the differences statistically, to connecting several results in a scientific paper, to reviewing it for publication, to undergoing criticism by the community, to assembling to a unifying theory, to writing about it in a technical report, to presenting it before a legislative committee. Of course, experimental errors (such as an uncontrolled experiment or mistaken protocol) and conceptual errors (such as mistaking correlation for causation or hasty generalization) are largely familiar territory for science educators. One benefit of a scheme based on an error type inventory is indicating how the social system of checks and balances or of communication is also seamlessly integrated into the process of science, a dimension too often peripheralized in science education (Allchin, 2004b). When the system of credibility fails, as in cases of fraud or gender bias, it is as much a part of science as a contaminated Neanderthal DNA sample, an uncalibrated instrument, or mistaken theoretical assumption. In this more expansive approach, an organized inventory of error types and their corresponding principles of scientific practice become a framework to guide educators.

The spectrum of error types is quite broad. So too, by extension, is the relevant NOS. Educators may thus need to reconsider the short NOS "consensus" list. While one may recognize several of the familiar NOS elements, such as the role of the cultural milieu, or theory-ladenness, or experiment versus alternative forms of observation, or inference from data (McComas & Olson, 1998), the taxonomy of errors helps give them a coherent epistemic structure (currently absent from the list). The diverse error types *relevant to the scientifically literate citizen or consumer* and a structure for conceptualizing them speaks to an NOS approach based on Whole Science, not a truncated list (Allchin, 2011a, 2012b).

TEACHING STRATEGIES AND RESOURCES

How, then, might one shape the conceptual aims of teaching about error and NOS into concrete classroom practice? First, teaching about the role of error and developing skills in error analysis is facilitated by historical cases studies. One can, of course, introduce error analysis in students' own inquiries. But the scope of error will be limited. It will be hard to profile confirmation bias or the limits of a single cognitive perspective. In addition, there is a strong affective component to "being wrong." Managing student emotions (in addition to the intellectual lessons) places extraordinary demands on the teacher. Consider, for example, a sample case from my teaching where emotion eclipsed an opportune lesson about experimental errors. The occasion was a college lab for nonmajors where students measured the cumulative activity of an enzyme. One student's data reflected a steady increase in reaction product (in a set of parallel samples), except for one time interval, where the level appeared to be zero. Had the product accumulated, then disappeared, then resumed its increase? Obviously not. Reasoning by context, the data point was in error. With the other data mapping a clear trend, one could safely exclude the one "measurement" with no harm to interpreting the results. Here (I imagined) was an exceptional teachable moment for learning about why scientists might throw out bad data (e.g., as Millikan did with some of his oil-drop runs; Franklin, 1981). Yet the student insisted that the measurement was correct. I offered a plausible explanation: one of the reagents for *measuring* the enzyme had likely not been added to that particular sample tube—easy enough to imagine with the crowded lab, the rushed time schedule, and the multitude of tubes to manage. This happens to real scientists, I noted: no fault, no blame. The trick was to notice the slip. Here, one could simply drop the unneeded extra data point as spurious. To my dismay, the student defended that he had *not* made a "mistake" (his term, not mine). Yet the student was unable to explain the anomalous graph, other than to declare that this was what was "observed." I sighed. The human mind is indeed emotionally complex. Teaching about error in students' own inquiries is not necessarily easy. When a historical figure makes an error, by contrast, one can address it with a sense of emotional distance. Yet the student can still engage in the intellectual challenge of finding flaws in experimental design or reasoning, and in imagining alternative explanations, or ways to test them.

Using history may seem to invite conventional lecture or passive storytelling. However, respecting ideals in active learning and inquiry mode, one should rather engage students in historical case studies in a guided inquiry mode (Allchin, 2011b; Hagen, Allchin, & Singer, 1996). As in all NOS lessons, students should reflect explicitly on their experience (Akerson, Abd-El-Khalick, & Lederman, 2000; Craven, 2002; Khishfe & Abd-El-Khalick, 2002; Scharmann, Smith, James, & Jensen, 2005; Seker & Welsh, 2005). Error is an integral part of recreating science in the making (Latour, 1987). Classroom narratives can trace a notable scientist down a path of error, with the students following along, perhaps reflecting on the status of the reasoning along the way. Students can *experience* error, shifting from an initially reasonable conclusion to an unexpected revised conclusion. The reasonableness of errors must be felt and internalized. But here the vicarious experience is emotionally less threatening.

Many historical case studies that involve error and exemplify this guided inquiry approach are already available. A sampling is provided in Table 3. All these cases illustrate concretely the "tentativeness" of science. They show that error occurs, even among highly regarded scientists. But even more, they render just how error occurs—and how it is remedied. Again, these are not just stories. They are inquiry cases that engage students in reasoning through the historical errors and then reflecting on how they occur. NOS is revealed through reflecting on a constellation of particular error types.

By contrast, treating errors as merely foolish or naive, or resulting from credulity or pathological self-delusion, risks alienating students. Admonitions to "be objective!" or

TABLE 3
Sample Guided-Inquiry Historical Case Studies Addressing Error in Science

Case	Source
Christian Eijkman: Misinterpreted beriberi as a bacterial disease	Allchin (2011c)
Stephen Gray: Misinterpreted the factors affecting electrical conduction	Henke and Höttecke (2010)
Hans Selye: Misinterpreted stress as a "general adaptation syndrome"	Singer (1996)
George Gaylord Simpson: Rejected continental drift in biogeography	Hagen (1996)
Joseph Priestley: Misinterpreted the role of light in photosynthesis	Nash (1957)
Amodeo Avogadro: Hypothesis relating gas volumes and weight was rejected for decades	Novak (2008)
Native American herbal remedies: Effective treatments rejected, false claims accepted	Leland (2007)
Richard Lower: Corrected William Harvey's claim that the heart provides a vital power to the blood (and thus its bright red color)	Moran (2009)
Joseph Proust, Claude Berthollet: Debate on the law of definite proportions	Strandemo (2005)
European geologists, 1800–1870: Reinterpreted evidence of Noachian flood (erractics, scouring) as due to glaciers	Montgomery (2010)
Joseph Weber: Claimed his instrument detected gravity waves	Haselberger (forthcoming)

"avoid bias!" are thus ultimately ineffective (Evans, 2002). They do not plumb the cognitive or social roots of error. Alas, this strategy is all too common in treatments of pseudoscience, fraud, and marginal science (e.g., Feder, 1999; Friedlander, 1998; Fritze, 2009; Park, 2000). Such approaches assume the "right" answer and impose a rationally reconstructed justification, rather than trace a conceptual path from the perspective of an errant believer (Allchin, 1995). The teacher aiming to develop a deep sense of NOS, then, will profile and contextualize the many sources of error through historical cases.

LEARNING PROGRESSION ON ERROR IN SCIENCE

Assuming such lessons are pursued, how might they be arranged serially to foster successively deeper levels of understanding about error and NOS? What is an appropriate learning progression (a notion that has gained prominence in recent years; e.g., American Association for the Advancement of Science, 2001–2004; Catley, Lehrer, & Reiser, 2005; Corcoran, Mosher, & Rogat, 2009; Duschl, Schweingruber, & Shouse, 2007; Smith, Wiser, Anderson, & Krajcik, 2006)? Here, I sketch one prospective sequence of increasingly more sophisticated ideas about error.

First, students might learn that scientists, even good scientists, can make mistakes. For example, Galileo is justly celebrated for his *Dialog on the Chief Two World Systems* in advocating a Copernican worldview. Yet the book's central thesis (betrayed in its original title, later censored) was that the tides are caused by the combined daily and annual motions of the Earth—and are physical evidence thereof. But tides are generated by the gravity of the moon and sun. Galileo was wrong. Galileo also developed a law for pendular motion. Yet this presumed universal law is a lie. It approximates results only for small angles. It neglects friction and possible unequal distribution of mass. No wonder that students cannot get their data in the lab to match the expected "universal" law. An idealization is inherently an error, even if a potentially fruitful one (Wimsatt, 2007). Galileo's achievements were many. But he was not free from error. Culture surrounds students with mythic depictions of scientists. Often, the ideal displaces the real. Teachers need to help temper the tendency to romanticize scientists by introducing a healthy dose of respect for error, even among famous scientists. Even at an early age, celebrations of scientists can be coupled with the acknowledgment of flaws. Greatness need not imply perfection. As noted above, teachers need to differentiate between *role models* and *real models*. Conveying the inevitable and acceptable *fact* of error in science is a first step.

Students may then be prepared to learn, second, the "how" of error. Errors are not just random events or lapses of personal integrity. They have identifiable sources. For example, Christian Eijkman's erroneous view that beriberi was caused by bacteria (rather than a nutrient deficiency) was rooted in prior expectations (confirmation bias). Those perspectives, in turn, were shaped by the recent emergence of germ theory and excitement about its potential to revolutionize medicine, as well as by patterns that indicated local contagion. A student can appreciate that anyone in Eijkman's position would tend to reach the same conclusion. Bächlin's error in X-ray wavelength (above) had discernible sources in a cascade of earlier measurement errors, originating in someone inadvertently using an incorrect value in a formula. The flurry of excitement on polywater in the late 1960s was ultimately traced to dirty glassware. Such cases prime an appreciation of the need to analyze claims for specific errors—not just to adopt a blanket skepticism. This lays a foundation for skills in analyzing claims in public and personal decision making, in a context of scientific literacy. This is where an inventory of error types becomes an important reference guide for educators.

In the absence of a clear analysis of sources, error is typically attributed—even among scientists—to psychological dispositions or undue social influence. A team of sociologists documented how one group of scientists from a contentious controversy interpreted each other's "errors." They variously alleged succumbing to charisma, a rhetorical "aura of fact," personal rivalry, dislike, and an "ostrich approach" of willfully disregarding the facts. They cited "intellectual inertia" and confrontation with "unorthodox" views. Others saw error as due to "prejudice, pig-headedness, strong personality, subjective bias, emotional involvement, naivety, sheer stupidity, thinking in a woolly fashion, fear of losing grants, threats to status and so on." (Gilbert & Mulkay, 1984, pp, 49, 65, 66, 71, 79, 81, 93, 96). "Thinking in a woolly fashion"? For the most part, these are not sources of error. They are convenient rationalizations for one's own position in the face of disagreement or criticism. They portray one's own view as rational and alternative views as irrational. One might well learn about the inherent cognitive tendency exhibited in such judgments, but some good examples of reasonable error (above) may be needed first as leverage. A deeper appreciation of the concrete sources of error and error types is needed to get beyond such simplistic dichotomies and to engage error in context.

Third in the prospective learning progression, students are ready to consider how errors are found and remedied. In popular conceptions, especially common in the lore of practicing scientists, science is "self-correcting." Yet this is an aggrandizing myth. Errors do not announce themselves, else they would hardly ever occur. Some errors can persist for decades. The racial and gendered errors of craniology lingered for decades, only to be transformed into errors about IQ testing (Gould, 1981). Kelvin's thermodynamic calculations of the age of the Earth held sway for decades, until the discovery of radioactivity as a source of heat exposed his erroneous assumptions (Hallam, 1989). Avogadro's hypotheses, too, lay abandoned for half a century (Guinta, 2001; Novak, 2008). Errors in science do not disappear merely with the passage of time. The belief that "the truth will out" is vague and unacceptable as an explanation (Gilbert & Mulkay, 1984, pp. 91–111). Finding errors requires scientific *work*.

Consider, for example, Joseph Priestley's experiments on plants and the "goodness of air." Priestley originally found that plants immersed in water yield a gas that helps restore the air for breathing. When he returned to those experiments later, he found, like others, that the effect was not consistent. Eventually, he noticed that light was required. So he pursued simple samples of water exposed to light (with no plants) and found that they, too, yielded the "purer," more respirable air. He concluded that his earlier claim was mistaken, and that the process was related to light, not plants. Ironically, it was the newly revised conclusion that was in error. Priestly also noticed that his vessels produced a green scum. He erred further in interpreting the green matter as a by-product of the enriched atmosphere. Jan Ingenhousz and others, however, saw a connection between the green scum and green plants. With further microscopic analysis, they realized that the scum was living algae. It was the green living matter that transformed the air—but only in the presence of light. They coupled their knowledge of plants as food and fuel to the sun's light, realizing that there was a further connection. Priestley had mistaken correlation and causation in two ways. To his credit, Priestley ultimately acknowledged his error, once the new explanation had been clearly demonstrated. But the alternative perspective of his peers had been essential to finding and remedying the error. Once again, identifying an error was coupled to a significant discovery, and it required work (Nash, 1957).

Errors are encountered and identified in various ways. Often, other scientists try to build on and develop earlier findings, only to find that they cannot do so. That leads to further work "isolating" the error. On other occasions, anomalies emerge by chance in an unrelated project—when someone notices the connection and pursues it. Other times, as in the case of Priestley, errors are profiled through alternative conceptual perspectives. Contrasting views help highlight deficits in the evidence or expose conceptual blind spots. Alternative perspectives—from various disciplines, biographical backgrounds, cultures, social classes, genders, etc.—enhance collective awareness. Ultimately, testing scientific claims against the evidence alone is not sufficient. Weeding out error frequently involves criticism and interaction. In terms of reliability of claims, then, the social dimension of science is just as important as the experimental (Harding, 1991; Longino, 1990; Solomon, 2001). That is an important perspective for educators who would dismiss sociology because they see it as depicting sources of error rather than a fundamental mechanism for remedying it (Allchin, 2004b; Finkel, 1992).

The final two "stages" of the prospective learning progression on scientific error involve more subtle and complex lessons, and hence may likely be reserved for more mature students. Both involve blurring the sharp dichotomy of right and wrong, discovery and error, fruitful methods and poor practice. The first of these is to recognize that errors may be productive or fruitful, even while being "wrong" in a sense.[5] The concept of phlogiston, for example, is often denigrated and even ridiculed as one of the most foolish concepts in the history of science. Yet using the concept of phlogiston, chemists predicted that hydrogen (inflammable air) could reduce metals. The concept of phlogiston facilitated discovering the role of light in the chemistry of plant growth. It opened the possibility of one metal reducing another (rather than depending on charcoal). It also stimulated investigation of the chemical properties of electricity, including its ability to reduce metals and acids, and of the galvanic apparatus (including electrolysis). Phlogiston was not so wrong headed, after all (Allchin, 1992; Carrier, 1991, pp. 29–30; Chang, 2009; Kim, 2008; Partington, 1962, Vol. III, pp. 268–270; Siegfried, 1964; Sudduth, 1978). Similarly, the notion that heat is a substance—caloric—led to the founding of calorimetry and the principle that heated gases all expand at the same rate. Adiabatic expansion of gases, apparently a major factor in the reasoning of the eight scientists who can lay claim to discovering the principle of the conservation of energy, was ironically first developed through caloric interpretations (Carrier, 1991, pp. 30–31; Fox, 1971, pp. 69–79; Holmes, 1985, pp. 160–183; Kuhn, 1958; Levere, 2001, pp. 75–77). These are pretty serious examples given conventional school science. They indicate how "the scientific method" as it has often been taught in schools—predict, test, decide—even as an ideal, is essentially impoverished. Many theories that have now been abandoned were once empirically successful. Some even made significant novel predictions that were indeed confirmed (Losee, 2005). Here may be a lesson for science teachers as much as science students.

The cases of phlogiston and caloric, along with others, may lead one to fuller discussion of models and scientific theories as selective representations or maps (see above). It is paradoxical, indeed, that the fluid model of electricity may prove correct *in a certain domain of phenomena*, even if scientists no longer regard electricity as a fluid. Models may prove useful and ostensibly true (within prescribed limitations), even if they are strictly "wrong" from another perspective. One might even find a place for phlogiston in a standard chemistry curriculum, both to help explain a certain set of phenomena and to open discussion about the nature of scientific theories and error (Mamlok-Naaman, Ben-Zvi, Hofstein, Menis, & Erduran, 2005; Scott, 1958). For a classroom inquiry-based lesson, see Allchin (1997).

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[5] Here I refer to "false" ideas that were widely accepted by a scientific community as "true." One could also comment on the potential of "false models as a means to truer theories"—either when a researcher acknowledges that the false assumptions as a heuristic or when an incomplete model is modified in yielding the next, rather than jettisoned entirely (Wimsatt, 2007, especially Chap. 4).

The second deeper lesson on error (last in the learning progression) is that, ironically, in many cases errors can be traced to the very same source that led to great discoveries. What leads to insight on one occasion is a blind spot on another. The potential for discovery and error seem inextricably coupled. For example, Darwin relied on Lyell's principle of uniformitarianism to develop his theory of the origin of coral atolls. It was accepted and helped launch his career. Not long after, Darwin applied the same kind of large-scale gradualist thinking to the "parallel roads of Glen Roy." Here, Darwin was wrong. He later acknowledged his "great blunder." In another instance, Darwin used a hierarchy of races to map out a theory on the evolution of morality. He saw the natives of Tierra del Fuego as mentally intermediate between orangutans and his peers in the British upper class. That enabled him to envision a transition, and present human evolution as applying to mental powers as well as anatomy. But the racist assumptions were ill founded, as noted in criticisms in letters from Alfred Russel Wallace (Allchin, 2009a). As illustrated in these two cases from Darwin's life, sometimes the very same concept or way of thinking that leads to discovery also leads to error. Unique viewpoints can foster insight in one context, while blinding one to alternatives in others. Paradoxically, if insights and blind spots are indeed two sides of the same coin—the expression of unique perspectives—then we cannot expect to prevent error in science. Nor would we want to, if we value new ideas. The cost of innovation seems to be the risk of failure. That is a potentially profound lesson, but one that might be reached only after a long series of reflections about error in science.

CONCLUSION

Pluto is no longer a planet. DDT, cyclamates, and Vioxx, all once deemed safe based on scientific study, are now viewed as unsafe, based on subsequent scientific study. Acupuncture, once dismissed as "quackupuncture," by contrast, is now regarded as effective for pain relief. In all these cases, science initially erred. Yet the revised conclusions are important for the scientifically informed consumer and citizen. If educators want students to understand and accept such changes in scientific consensus, rather than dismiss science itself as arbitrary or capricious, they must teach the limits of science and the foundations of scientific error. Indeed, the ability to interpret such authentic cases may well be a way to assess knowledge of NOS (Allchin, 2011a). Such knowledge of NOS seems equally important in recognizing that other purported scientific claims—about serial dilution of homeopathic remedies, "worlds in collision," so-called Intelligent Design, or anthropogenic climate change as a fiction—exhibit critical sources of error, and may be rejected as not meeting appropriate standards of evidence and credible expert testimony. Teaching about error is also about teaching about its inverse, reliability in science.

The current status of such knowledge about NOS and the role of error may be illustrated in a recent letter to the editor of a major newspaper:

> Thank you for publishing .... on the recent experiment on neutrinos that casts doubt on the entire modern theoretical framework of physics. It is a reminder that even the most accomplished among us are limited and subject to error. And I hope that this news might inspire a little humility in those who claim, in the name of science, that theories predicting calamity caused by man-made climate changes are settled fact and not subject to debate. (Prescott, 2011)[6]

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[6] The irony here, of course, is that within half a year, the experimental results themselves were discredited—due to a loose cable (Cartlidge, 2012). A little humility, indeed.

Over the course of a few months, there were similar sentiments expressed in other letters to the same paper—arguing from the demise of Pluto to the inherent uncertainty of evolution and from changing policy on food dyes to vaccines as a candidate cause of autism (despite discredited studies) (Allchin, 2012b). One even referred to "the wisest science teacher I know" who "told his class that science proves nothing true; it can only prove things false" (Juel, 2011). Here, political positions on climate change, evolution, and vaccines have been informed by views—in these cases, quite naive views—about error in science. Such beliefs indicate the need for better understanding of the nature of scientific errors. Educators need to acknowledge that vague hand waving about skepticism, objective thinking, or science as "tentative" or "self-correcting," or even about falsification as a simple basic principle, are inadequate for developing functional scientific literacy. Understanding potential sources of error and error types (Table 2) is integral to complete science education.

APPENDIX: BIBLIOGRAPHY ESSAY ON ERROR IN SCIENCE

Here I survey briefly of some of the main scholarly sources on error in science that can prove valuable to science educators.

Four volumes highlight the philosophical dimensions of error:

- Mayo, D. (1996). Error and the growth of experimental knowledge. Chicago: University of Chicago Press.
- Losee, J. (2005). Theories on the scrap heap: Scientists and philosophers on the falsification, rejection and replacement of theories. Pittsburgh, PA: University of Pittsburgh Press.
- Holton, G., & Mack, A. (Eds). (2005). Errors: Consequences of big mistakes in the natural and social sciences. Social Research, 72, 1.
- Hon, G., Schickore, J., & Steinle, F. (2009). Going amiss in experimental research. Boston Studies in the Philosophy of Science, No. 267. Dordrecht, The Netherlands: Springer.

Mayo's book addresses error statistics as a core concept, from which Mayo explores many traditional philosophical problems, such as underdetermination (the Duhem–Quine problem), Popper's severe tests, hunting and snooping, and an analysis of Peircian error correction and induction. Educators may appreciate here the pervasive role of sampling error and the statistical reasoning for accommodating it. Mayo also profiles the strategies that scientists deploy to detect, address, or counterbalance error when it cannot be eliminated due to the limits of experimental design. Losee's volume takes a clever twist on the usual philosophical question of why theories are *accepted* and asks why they are sometimes *rejected*. He examines numerous historical cases and such issues as the role of falsification, prediction (vs. accommodation), and personal thematic style. Here are plentiful concrete examples of "tentativeness" in science, including descriptions of how scientists "discovered" their earlier errors. The special spring 2005 issue of *Social Research* is described by Holton in his introduction:

> At first blush, "science" and "error" seem to be polar opposites—the one a heroic pursuit of provable and widely sharable truths, the other a miserable exemplar of human frailty. (p. vii)

Holton summarizes the spirit of the volume that any heroism in science is largely due to the dogged struggle with errors. There are insights, to be sure,

> But on the way to those rare eureka moments, practitioners of science know well that the path is strewn with hurdles and pitfalls, costly detours, with minor and major blunders and gremlins in the experimental equipment or in the theoretical presuppositions. (p. viii)

The cases in this collection illustrate these themes and provide detailed information for prospective case studies for the classroom. Finally, the collection on *Going Amiss* is based on a symposium largely limited to just the realm of experiment. It underscores that in addition to outright errors, researchers may encounter unexpected obstacles or, in some cases, opportunities. For example, for many years, meteorologists confronted the "height catch problem" with discrepancies between rain gauges placed at different distances off the ground. Error, or uncertainty, may be found even in something so simple as an observation or measurement.

There are also a handful of individual philosophical and sociological papers that are particularly significant:

- Suppe, F. (1998). The structure of a scientific paper. Philosophy of Science, 65, 381–405.
- Hon, G. (1989). Towards a typology of experimental errors: An epistemological view. Studies in History and Philosophy of Science, 20, 469–504.
- Allchin, D. (2001). Error types. Perspectives on Science, 9, 38–59.
- Star, S. L., & Gerson, E. M. (1986). The management and dynamics of anomalies in scientific work. Sociological Quarterly, 28, 147–169.
- Gilbert, G. N., & Mulkay, M. (1982). Accounting for error: How scientists construct their social world when they account for correct and incorrect belief. Sociology, 16, 165–183.

Suppe analyzes the structure of arguments in a large sample of scientific papers. His surprising result is that they do not reflect the canonical hypothetico-deductive method, often portrayed as "the" scientific method. Such an argument structure discounts the importance of the methods section, for example. A fine-scaled parsing of each step of the typical argument shows that the scientific paper is structured around the many possible sources of error. Attention is given to each possible alternative interpretation of the evidence. Namely, the paper argues its conclusion stepwise, addressing each potential flaw in procedure, observation, and reasoning. This focus on error in argument is especially relevant given recent views on the role of scientific argument and justification in teaching NOS. Hon and Allchin address the classification of errors in science, as noted in the main text. Sociological studies of error in science are few, despite the vast literature on scientific controversies. A notable contribution is Star and Gerson's anthropological analysis of error. They describe error *behaviorally*: as an interruption of work flow. Their categories of error, nonetheless, tend to match the philosophical analyses noted. Gilbert and Mulkay discuss the attribution of error by other scientists. In particular, they show that interpreting error is just as theory-laden as interpreting evidence.

There are also numerous historical treatments. Some now classic cases, where the authors also frame the history in terms of its more philosophical lessons, include

- Franks, F. (1981). Polywater. Cambridge, MA: MIT Press.
- Gould, S. J. (1981). The mismeasure of man. New York: W. W. Norton.
- Kottler, M. J. (1974). From 48 to 46: Cytological technique, preconceptions, and the counting of human chromosomes. Bulletin of the History of Medicine, 48, 465–502.

- Nye, M. J. (1980). N-rays: An episode in the history and psychology of science. Historical Studies in the Physical Sciences, 11, 125–156.
- Gould, S. J. (1985). The freezing of Noah. In The flamingo's smile (pp. 114–125). New York: W. W. Norton.

Other general surveys include

- Buchwald, J. Z., & Franklin, A. (Eds.). (2005). Wrong for the right reasons. Dordrecht, The Netherlands: Springer.
- Darden, L. (1998). The nature of scientific inquiry. Retrieved March 26, 2012, from www.philosophy.umd.edu/Faculty/LDarden/sciinq/index.html.
- Allchin, D. (2008). Nobel ideals and noble errors. American Biology Teacher, 70, 389–392.
- Allchin, D. (2009). Celebrating Darwin's errors. American Biology Teacher, 71, 116–119.

These by no means exhaust the historical accounts of particular episodes of error.

Finally, a number of semipopular volumes in psychology focus on more general cognitive errors, such as confirmation bias, whose relevance to science is easy to appreciate:

- Kahneman, D. (2011). Thinking, fast and slow. New York: Farrar, Straus and Giroux.
- Gilovich, T. (1991). How we know what isn't so. New York: Free Press.
- Sutherland, S. (1992). Irrationality: Why we don't think straight. New Brunswick, NJ: Rutgers University Press.
- Shermer, M. (2002). Why people believe weird things (2nd ed.). New York: W. H. Freeman/Henry Holt.
- Hallinan, J. T. (2009). Why we make mistakes. New York: Broadway Books.
- Schulz, K. (2010). Being wrong: Adventures in the margin of error. New York: Harper Collins.

A few philosophers have begun to articulate the implications of such cognitive limitations for scientific practice and scientific discovery:

- Bechtel, W., & Richardson, R. C. (1993). Discovering complexity: Decomposition and localization as strategies in scientific research. Princeton, NJ: Princeton University Press.
- Wimsatt, W. C. (2007). Re-engineering philosophy for limited beings. Cambridge, MA: Harvard University Press.

That is, cognitive science may inform educators not just about how learning occurs, but also how the inherent constraints in human thinking affect the generation of scientific knowledge.

Finally, another two volumes focus, with a more journalistic tone, on a socially based error—fraud:

- Broad, W., & Wade, N. (1982). Betrayers of the truth. New York: Simon and Schuster.
- Judson, H. F. (2004). The great betrayal: Fraud in science. Orlando, FL: Houghton Mifflin Harcourt.

For more on conceptualizing fraud as an error type, see the main text.

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