

TO ERR IS SCIENCE

PREFACE

- To err is science. That may seem startling, or puzzling—or even heretical. But in this book I show, through plentiful examples from history and contemporary science, how error is integral to learning and progress in science, and, more pragmatically, just how scientists may fruitfully manage the errors that they inevitably encounter.

- Traditionally, we turn to science for reliable knowledge. The epitome of fact. But scientists occasionally get entangled in the “wrong” answers, imagining them to be fully justified. There are abundant familiar examples from history—the Earth as the center of the Solar System; the immutability of species (without evolution); the fixed position of the continents in the Earth’s crust (without drift); disease as caused by “bad airs” or imbalanced “humors” (with no notion of “germs”); water and air as chemical elements; and so on. In this book, I describe scores of cases of error—in chemistry, in biology, in physics, in geology, in medicine, in astronomy, and elsewhere. If we want to understand science and its trustworthiness, then we surely need to explore why and how science errs.

- Ironically, perhaps, finding errors and remedying them is also science. To err is human (so they say). And science is a human enterprise. So, it should not seem surprising that scientists might err. But unlike many other fields, when errors emerge, scientists attend to them. As a result, they ultimately develop more reliable knowledge, as well as methods that help them avoid the same errors in the future. Scientists learn from error. So, it seems of general human interest to know how scientists falter, and how they find their way again.

- Indeed, a concerted study of error in science yields some unexpected conclusions. For example, “negative” knowledge has a “positive” role. Understanding particular errors contributes to the overall growth of knowledge—even when some earlier concepts are abandoned as “wrong.” Accordingly, we might reconceptualize knowledge — not as “true” *versus* “false,” but embracing them both as forms of knowledge. That is, we should contrast true-or-false (the known) to uncertainty (the unknown).

Errors lead to improving methodologies at multiple levels. Thus, standards of proof escalate. The quality of knowledge improves. Looking ahead, we can make scientific practice even more effective through more systematic attention to error. We can nurture a habit of deepening existing knowledge by deliberately probing for possible unresolved sources of errors.

- This book thus will be valuable to anyone concerned with the trustworthiness of science. It is for everyone who reads *Nature* or *Science* magazine. Or who listens to *Science Friday*. It is for

science graduate students and other aspiring scientists, science teachers, and science administrators. Practicing scientists, too. And judges and legislators. And science journalists. It is relevant to scholars in Science Studies—historians, philosophers, sociologists, ethnographers, and cultural critics. It is also for anyone who thinks carefully about how science informs public policy or personal decision making. It offers an intimate glimpse into the nature of science, essential for the task of assessing the reliability of scientific claims, either as an expert, or as a outsider who must rely on and trust the scientific experts.

- Science is work. Challenging work. Stereotypically, scientists follow a widely touted “Scientific Method,” which supposedly leads unerringly to a triumphant discovery. However, as often as not, the results are unexpected or ambiguous. No easy “aha!” moment. What happens then?

Different experiments may yield apparently contradictory results. Measurements may not align with theoretically predicted values. Evidence may be ambiguous and susceptible to multiple interpretations. Various incongruences arise. Discordances. Anomalies. Incompatible explanations. Something is “wrong.” (Something.) There is an error lurking somewhere. This book is about those occasions.

For me, this is when the work of science *really* begins. How can one reconcile the conflicting findings? What further observations will help resolve the uncertainties? It requires creatively designed investigation. Collecting more relevant data. Imaginatively reconfiguring all the evidence. Back to the field, back to the lab. To a surprising degree, perhaps, scientists may spend more time troubleshooting problematic results than simply testing the hypotheses they originally set out to confirm or disconfirm. But what comes from that meandering trajectory is genuine discovery — learning something no one suspected before.

- Error is not a wholly unfamiliar topic across a broad range of contexts. But I hope to introduce some novel perspectives to each. In particular, I hope my approach is both more comprehensive and more systematic, and able to help unify the currently scattered and disparate views.

- For example, error is a topic of informal conversation (and gossip) among practicing scientists. One familiar with the current controversies appearing in the pages of major journals like *Nature* or *Science* might suppose that this is another book on the “reproducibility crisis” and the documented failures to replicate famous experiments. Another doomsday warning that (according to one prominent critic) “most scientific findings are false.” Or, one might suppose, it is about the scandalous rise of misconduct and “questionable research practices” — cold fusion, organic semi-conductors, room-temperature superconductivity, and other such outlandish claims. But I have very little to say about these topics, other than to note that they find a relatively minor place in the larger topic of error in science. Viewing error more holistically, one can accept error as “normal.” No need to cry “fraud” at every turn. No need to fret every time a replication fails.

At the same time, one might fruitfully engage the new wave of concern about reliability and address how we reckon with scientific error. Here, I shift focus from individual studies and published reports to the social and institutional level. I explore more fully the mechanisms for mitigating errors and for addressing the residual errors (which cannot be eliminated entirely). Namely, diagnose the error types and isolate precisely where more evidence is needed. Possibly use those lapses to craft new methodological tools and remedies. This book thus acknowledges error as a regular feature of scientific practice and seeks to articulate a pragmatic approach to

managing those errors. History, well interpreted, can inform more effective practice.

- Error is a topic, too, among philosophers of science. Some muse on the history of science. By observing that past theories seem to eventually fall by the wayside, some conclude that current theories must inevitably be wrong, as well. They even honor their dire view with its own special label: the “pessimistic induction.” Much ink has been spilled arguing its status: why it is most assuredly true and (equally) why it is most assuredly false. In this book, I have no interest in engaging this somewhat metaphysical debate. I do not share the unfruitful pessimism, nor the crippling skepticism. (Nor do I subscribe, on the other hand, to a romanticized blind faith in science.) Rather, I have tempered confidence that scientists can—and do—find a wide spectrum of errors, probe each other’s results, and vet them with varying degrees of confidence. But this new view requires extended analysis based on many examples—and on respecting a more nuanced view of history. We need a full fledged philosophy of error — developed throughout this book.

Other philosophers have ventured modestly into this challenge. As yet, however, no comprehensive account or structure for understanding both error and (equally) its remedy has emerged. How are they both part of the same overall process? Here, I provide a sequel to and reconciliation of positivist traditions and Kuhnian perspectives. I acknowledge the role of negative knowledge and emphasize its productive role in guiding further science. As knowledge of error grows, standards of proof become more stringent, and the quality of scientific knowledge rises accordingly—an underappreciated form of progress.

- Historians of science, too, sometimes delve into error. In former times, this was to show how science had progressed, triumphing over error. Much of that historiographic style has fallen into disrepute as unduly distorted—more a judgment than a professional form of insightful historical analysis. But the romantic view still lingers in popular accounts, parading science as the pinnacle of culture. To those who subscribe to that idealization, they will find a more sobering (but also more human and compelling) perspective here. Our first responsibility should be to understand why each error happened, in historical context — without trying to either “blame” the scientists or, conversely, “excuse” them. Those inclined to regard error as inherently “pathological,” or an occasion for ridicule, will find no solace here. This book subscribes to good, contextualized history, which provides an important resource for engaging with the very real role of error in the nature of science.

Other historians have written about error more sympathetically, documenting the perspective of historical scientists in their original context. But these many isolated accounts have yet to be brought together, and treated systematically for how they might inform a deeper view of the nature of science, or how they might enrich contemporary scientific practice. This book takes up that task.

- Discussion of error is found among science educators, as well. For well over a half-century, educators have aimed to teach about the “nature of science,” or how science works, in order to inform students as citizens and consumers. Educational debates fester, and ideological fashions wax and wane. Yet one principle has remained central throughout: that science is “tentative.” That is, it is fallible. Provisional. Contingent. Subject to conceptual change. Namely, scientists can err. In a particular irony, however, the educators are also among the first to defend science as indisputably reliable. It is a “special” way of knowing, distinctive for its experimental methods,

respect for empirical evidence, and so on. Science seems to be “tentative” and “durable” both: an equivocal assertion — and highly confusing.

Here, I hope to offer a way to resolve this tension, by explaining both how (and when) scientists have indeed erred and how (and when) they have found and resolved their errors. Learn by example and reason from concrete, fully contextualized episodes of error, I say. Thus, the book is replete with historical cases. They demonstrate how science works. And also how it sometimes doesn't work (and why). And how it remedies itself again. A science *of* science, perhaps?

- Science advocates, too, may admit that—at the margin—science is not perfect and that individual scientists, at least, do sometimes make errors. (Sometimes!) But they typically add hastily that science is *self-correcting*. No cause for alarm. No need to inquire further. But just *how* science is self-correcting is less clear. When considered historically, the two most commonly cited mechanisms — peer review and replication — prove weak indeed (more on that in the chapters ahead). We need to temper the blinkered rhetoric of a “self-correcting” mythos. Indeed, acknowledging the limits of any particular scientific claim will help articulate more clearly what level of trustworthiness it has secured.

- Error in science is a favorite topic, too, of anti-science critics and purveyors of scientific disinformation. Creationists, anti-vaxxers, climate change naysayers. Every shadow of doubt or minor inconsistency seems a rationale to jettison the whole scientific enterprise. However, if they want a book that will help them “dis” modern science, they should look elsewhere. Every error is an indicator that scientists are alert and vetting their claims—and actively continuing to learn. Errors are not vulnerabilities, whereby the trustworthiness of science instantaneously collapses or invariably unravels. This book champions errors, ironically, as a strength and as a hallmark of good, active science.

- In some ways this book is an alternative history of science. It irreverently traverses the centuries, and hops blithely from one field to another. It is episodic, focusing on isolated cases, with little regard for tracing long lineages of conceptual development. It ricochets between grand theories and almost trifling details of lab practice that might hardly seem worth noticing. And it treats them all as informative. Namely, less notable (possibly obscure) discoveries may tell us just as much about the nature of science as the more familiar, prominent ones.

At first, these cases may seem random. Arbitrary bits of science wandering aimlessly through history. However, each episode involves a historical error. And each holds a clue to how to interpret those errors on a larger scale.

The eclecticism is part of a mindful effort to embrace the whole of science, from its micropractices to its revolutions, from its abstruse concepts (of concern possibly to only a handful of specialists) to its concrete applications in the ordinary lives of consumers and citizens. Science encompasses them all. A fitting portrait of science and how it works is thus not limited to certain occasions or contexts.

Some casual readers may regard this book as just a series of fascinating anecdotes — fodder for entertaining conversation, no more. That would itself be a mistake. All the historical cases have an important philosophical lesson. Every error in science is a paradoxical discovery, of sorts: learning that something that was once deemed true, is no longer viewed as such. And that typically has led us to discovering something else as true instead. This exploration of error

in science is, ultimately, a story of science itself.

Despite the somewhat kaleidoscopic nature of the historical adventure, however, I have tried to organize the scenes to tell a somewhat unconventional—but, I hope, still epic—tale. The reader (I trust) will become more acquainted with how scientists really work, even if perhaps from the inside out. Ah, to err is science.

- Ultimately, this book endeavors to engage the reader in a thoughtful reflection about error in science. It is steeped in history and sociology of science, and permeated with philosophical analysis and lore from the lab.

I describe over 200 cases of error, both historical and recent. They are catalogued in the Appendix: a sort of historical bibliography. Exploring the details of these cases—where error has been fully resolved—is critical to fully understanding the nature of error in science. The case studies constitute the evidence for how science works — not through idealized abstractions or argument, but as observed in authentic practice.

The text shifts between general observations about error in science and the specifics of the cases, which help illustrate and inform the commentary. The historical cases represent the spectrum of scientific disciplines — chemistry, physics, biology, medicine, astronomy, geology, and others. Addressing the broad range of fields is part of an effort to responsibly document errors across all scientific practices and to reflect the generality of my conceptual analysis. The diversity also helps respect a diversity of readers, each with their own sensibilities. They are also included for a sense of completeness and to foster a stronger sense of the ubiquity — and relevance — of error across all the scientific disciplines.

- The book is shaped, in part, by my own background participating in several research projects — on tree gap succession in the forests by the Chesapeake Bay, on sexual selection of flowers in the Rocky Mountains, on species turnover in a tropical rainforest in Panama, and on the evolution of “information-center” foraging among honeybees and other animals. It is further informed by my work as a historian of science, a philosopher of science, and science teacher. And by many, many informal conversations with working scientists, who encounter error in their everyday practice.

Even with my decades of experience in and around science, errors in science never cease to fascinate me. Let this book be an invitation for you to participate in exploring that world: how errors happen, how they are found, and how they are remedied.

- Ironically perhaps, this book—with its provocative title — is a *celebration* of error in science. That may seem counterintuitive at first or, worse, perverse. If a central aim of science is to produce reliable knowledge, how could error be anything but an annoyance and a distraction along the way? I hope to show, by contrast, how error is integral to learning and to increasing the reliability of knowledge, and thus to the very aims of science. Yes, to err is science.

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CHAPTER SUMMARIES

Preface

To err is science. That might seem to pose a problem for public policy and personal decision making, where we rely on science for trustworthy knowledge. But scientists also find errors and remedy them—and learn from them. While scientists, historians and philosophers have commented on error, we need a comprehensive and systematic approach—a philosophy of error—to organize our understanding and guide how scientists manage error in practice.

ERROR ITSELF

1 Honest Error

Vestiges of errors haunt our scientific terms. Concepts change. Error is exposed. Knowledge inevitably grows by trial and error, so should we not celebrate errors as part of the process? Even the most famous scientific heroes from history and Nobel Prize winners have erred. We must abandon the heroic mode that treats error as pathology and instead accustom ourselves to honest errors. By adopting an analytical (rather than a judgmental) stance, we can perhaps learn more about how science works and how to shape more reliable practices. Well informed history is an indispensable resource.

2 What Counts as Error

What do we mean by error? Defining error proves to be surprisingly difficult, because the identification of an error straddles different times, contexts, and bodies of evidence. I focus on the change in justification—from a claim once considered justified to its later status as unjustified. This cryptic shift will guide our analysis, and invite us to think more fully about what is meant by scientific justification. Some errors seem trivial—good for a chuckle, perhaps. So, does the scale of the error matter—whether it is a blunder, a big whopper, or just a small blooper? An important dimension of interpreting error is not the content of the claim itself, but the epistemic posture towards or commitment to the justification of the claim in question. Also how do the connotations of the terms “right” and “wrong” shape our thinking about the epistemic versus moral dimensions of error? Error is definite, even if a negative claims perhaps. Error thus differs from uncertainty or vague disclaimers of “tentativeness.”

ERROR TYPES

3 Sources of Error

Experimentalists frequently refer to *sources of error*, the factors ranging from dirty glassware and contaminated samples to confounding variables and mistaken assumptions that can produce misleading results or faulty conclusions. Here, I generalize this concept to the whole process of science, applied at three levels: observational, conceptual, and discursive. What kinds of errors are there? At each level, we may survey history to identify general *error types*—the many potential pitfalls that might ultimately guide more reliable scientific practice. They support assembling an *error inventory* as a reference guide.

4 Observational Errors

Observational errors arise in laboratory experiments, field studies, or other forms of measurement or collection of data. They include material errors, instrument errors, human perceptual deficits, observer bias, observer effects (including artifacts), and various forms of misframing—sampling bias, sample size, incomplete sampling, proxy variables and heuristic gaps, and confounders.

5 Conceptual Errors

Conceptual errors arise in reasoning about observations at many levels, from processing data and analyzing them statistically to conventional logic (and its fallacies) and interpretive practices (some shaped by heuristics and inherent cognitive biases). They include overgeneralizations, faulty assumptions, theory-laden judgment and confirmation bias, heuristic gaps, cognitive lapses, unaddressed alternatives, cryptic alternatives, and various forms of cultural bias—such as those based on religion, gender, race, class, or politics.

6 Social-Level Errors

Errors also occur at the social level, in the customary discourse among scientists. That is, there are institutional, even if informal mechanisms of “quality control” in the scientific community. They are designed to regulate accurate and full reporting, expertise, theoretical bias, and deception. Error types include communal confirmation bias, communal cultural bias, ineffective peer review/publication, credibility bias and fraud, and conflict of interest. Consensus arising from reciprocal criticism is thus an important benchmark.

THE SELF-CORRECTING MYTHOS

7 The Truth Will Out?

Widespread folk rhetoric maintains that science is self-correcting. “The truth will out”—at least “eventually” or “with time.” However, five historical observations—long-standing errors, compounded errors, error cascades, rejection of corrected theories, and happenstance—all challenge such views and indicate qualifications are needed.

8 The Limits of Replication and Peer Review

Proponents of the self-correction thesis typically appeal to two mechanisms that purportedly prevent error: peer review and replication. A close examination of these two processes in actual practice indicates that their roles are acutally quite limited. Errors must be corrected by other means.

REMEDYING ERROR

9 From Incongruence to Error

How, indeed, are errors remedied? Errors are errors in part because the flaws in their justification are hidden. Exposing them, and ascertaining their status as errors requires *work*—epistemic work, not the mere passage of time. The first step is an awareness that something is awry. Researchers may encounter *incongruences*: (1) in their observations (*discordances*), (2) in the match between theory and observations (*anomalies*), or (3) in

alternative theoretical interpretations (*ambiguities, or disagreement*). The next step is to *isolate the error* by tracing it to any of the error types. Controlled experiments are especially important here.

10 More Evidence

Incongruences are inevitably resolved and errors definitively localized with further information. But how does such evidence arise? More evidence may emerge through (at least) increased sample size, wider scope, the increased resolving power of instruments, new technology, filling of heuristic gaps, contingency (accident), or new conceptual horizons. Motivational context and resources (funding) are also important at a concrete, practical level. The growth of knowledge poses an epistemic puzzle: how can new information upend a verdict once deemed to be justified by fewer facts?

ERROR IN SCIENTIFIC PRACTICE

11 Insights & Blind Spots

Individual perspectives (or “biases”) may generate blind spots and error. But they also seem to underlie important insights and discoveries. Bias can be fruitful, as well as misleading. A conundrum. The cost of innovation is the risk of failure. Science can harness the variation in standpoints through a social system of checks and balances. Mutual analysis from complementary perspectives helps expose adverse bias and filter out corresponding error.

12 Managing Error

A deeper awareness of error in science may underscore that the practices of science are focused as much on regulating sources of error as on “seeking the truth.” We benefit from *negative knowledge*. Indeed, most of the familiar methodological norms of science have traceable historical roots, based on encounters with certain error types. Errors may seem to threaten the notion of scientific progress, but by focusing on the escalating standards of proof, we may acknowledge growth in the quality of knowledge, even if errors lead us to abandon some concepts or theories. We may articulate field-specific *error repertoires*, which can assist in mitigating future errors and in diagnosing problems in research. The familiar concept of checklists may be adapted in envisioning a series of *checkpoints*, occasions where reviewing sources of error seems especially appropriate. A deeper awareness of error types may also lead us to a view that confirming evidence alone is insufficient. To deepen reliability, we need *error probes* to actively search for possible loose ends and qualifications. “Nothing’s concluded until error is excluded.” All these projects may foster further study in the *Philosophy of Error* and in developing *Error Analytics*, tools for managing errors in everyday scientific practice.