

## NOTES

Some of the sources and resources mentioned here are available to anyone online; some are rather difficult to get hold of if you don't have a university affiliation. I recommend checking authors' web pages for "preprints" (that is, near-final versions of papers whose definitive versions may be behind paywalls). Preprints of my own papers are on my website at <http://www.strevens.org>. A helpful resource for philosophical topics is the Stanford Encyclopedia of Philosophy (<http://plato.stanford.edu>).

### INTRODUCTION: THE KNOWLEDGE MACHINE

- 2 to its stock of knowledge, scarcely at all: There are honorable exceptions: mathematical astronomers in Babylon and Greece developed theories that accurately predicted the movements of the sun, moon, and planets, and the Greek thinker Archimedes made substantial discoveries in hydrostatics, or the science of floating, immortalized in his wild discoverer's cry "Eureka!"
- 6 "There was no such thing as the Scientific Revolution": The first sentence of Shapin's book *The Scientific Revolution*. The artful discordance between Shapin's title and his first sentence illustrates two ways to use the term *Scientific Revolution*. On the one hand, it is the name for a certain sequence of events—the observation of Jupiter's moons, the discovery of the circulation of blood, the articulation of Newtonian physics—whose occurrence is a matter of historical record. On the other hand, and more contentiously, it is the name for a presumed new intellectual or social movement that precipitated those events. Shapin writes the social history of one while denying the existence of the other.
- 6 "still shrouded in darkness": Feyerabend, *Science in a Free Society*, 73.

### CHAPTER 1: UNEARTHING THE SCIENTIFIC METHOD

- 13 a condemnation of totalitarianism: Popper, *Open Society and Its Enemies*, published in 1945.
- 13 perhaps the only human activity: Popper, *Conjectures and Refutations*, 293.
- 13 his philosophical masterpiece: *The Logic of Scientific Discovery* was published in German in 1934; it first appeared in English 25 years later, in 1959.
- 14 "incomparably the greatest": In a BBC radio interview, cited by Magee, *Popper*.

- 14 "the war years and their aftermath": Popper, *Unended Quest*, 13. The quote that follows is from p. 32.
- 15 "freedom is more important than equality": Popper, *Unended Quest*, 36.
- 15 "I remember only": Popper, *Unended Quest*, 37. The quote that follows is from p. 38.
- 17 "there is no intellectual difference": Russell, *History of Western Philosophy*, III.1.17.
- 18 "If the redshift": Quoted approvingly by Popper in *Unended Quest*, 38.
- 19 "Scientific theories, if they are not falsified": Popper, *Unended Quest*, 79.
- 19 there is no point in trying to gather evidence: Popper did think that scientists should accord a certain respect to theories that have withstood **severe testing**. He said that such theories were "well corroborated," but held to his **anti-inductive** view that we have **no more** reason to believe a well-corroborated theory than a theory that has not been tested at all.
- 20 "Let our conjectures . . . die in our stead!": Popper, "Natural Selection and the Emergence of Mind," 354.
- 20 "There is no more to science": Cited by Magee, *Popper*, 9. See also Mulkay and Gilbert's "Putting Philosophy to Work," a sociological study of Popper's influence on scientists' methodological theory and practice.
- 20 "I learned from Popper": Eccles, "Under the Spell of the Synapse," 162.
- 21 the anatomist Solly Zuckerman: Nicholas Wade describes the episode in *The Nobel Duel*, p. 54. The brain in question supposedly lacked a channel between the hypothalamus and the pituitary that, according to Harris, was essential to ferrets' coming into heat, which Zuckerman's ferret had nevertheless done. Harris pointed out the many ways in which this one-off case might be misleading. He won the argument and is now regarded by many as the "father of neuroendocrinology" for his theory of hormone-driven communication within the brain.
- 22 "I understood at last the problem of induction": The story is told by Ronald Giere in his book *Science without Laws*. He attributes it to the philosopher Andreas Kamlah, who, he reports, "knew neither of its origin nor any evidence that it might be true." In my experience, such anecdotes are almost always urban legends, but in the spirit of inductive skepticism, I decline to disbelieve this one on those grounds.
- 22 Morris recalls that Kuhn: As related in *The Ashtray*. Morris writes, "I had imagined graduate school as a shining city on a hill, but it turned out to be more like an extended visit with a bear in a cave" (p. 9).
- 22 "a neurotic, insecure young man": The quotes are from the interview with Kuhn in *The Road since Structure*, respectively pp. 280 and 276.
- 23 "Suddenly the fragments in my head": Kuhn, "What Are Scientific Revolutions?," 9.
- 24 they would find it incomprehensible: Kuhn talks about the grip of the paradigm in many different ways. Sometimes, especially early on in *Structure of Scientific Revolutions*, the paradigm is merely a set of assumptions that scientists take for granted—albeit assumptions that are strictly socially policed. (Scientists who dare to dissent from the paradigm "are simply read out of the profession, which thereafter ignores their work" (p. 19).) Later in the book the paradigm is said to cause "an immense restriction of the scientist's vision" (p. 64), and by the end of the book scientists with different paradigms "practice their trades in different worlds" (p. 149). In my exposition of Kuhn, I emphasize his stronger statements about the paradigm's hold on scientists' minds.
- 26 arguably the first scientific revolution: On the question of whether Greek astronomy was sufficiently scientific that the transition from Ptolemy to Copernicus con-

- stituted a lower-case scientific revolution, Kuhn was a little vague. The same is true for the transition from special creation to Darwin.
- 28 "Normal science . . . is predicated": Kuhn, *Structure of Scientific Revolutions*, 5, 52.
- 28 some visionary "deeply immersed in crisis": All quotes in this paragraph are from Kuhn, *Structure of Scientific Revolutions*, 90.
- 29 "conversion experience": Kuhn, *Structure of Scientific Revolutions*, 150.
- 30 "When paradigms enter": Kuhn, *Structure of Scientific Revolutions*, 94.
- 30 Perhaps if you had two brains: Would your two brains understand one another well enough to negotiate a winner? Kuhn suggested that there is no common methodological, conceptual, or linguistic framework that they could use to discuss their differences—a predicament he named "incommensurability." For many years he worked on a definitive treatment of the topic. It never appeared.
- 30 the Aristotelian and the Newtonian live in different worlds: That is the thrust of the controversial Chapter 10 of *Structure of Scientific Revolutions*.
- 30 "as in political revolutions": Kuhn, *Structure of Scientific Revolutions*, 94.
- 30 "mob psychology": Lakatos leveled this charge in his long and influential 1970 essay "Falsification and the Methodology of Scientific Research Programmes," 178.
- 32 later paradigms tend to have more predictive power: This is not to say, as Kuhn emphasized, that a new paradigm can predict everything forecast by its predecessor. Predictively speaking, it may be two steps forward and one step back—but that still adds up to one step forward.
- 34 the 1977 Nobel Prize: Guillemin and Schally split the prize with Rosalind Yalow, who was honored for a different but related achievement. An engaging account of the contest between Guillemin and Schally can be found in Nicholas Wade's *The Nobel Duel*.
- 34 "immense amount": Latour and Woolgar, *Laboratory Life*, 120.
- 34 "Nobody before had to process": Quoted in Latour and Woolgar, *Laboratory Life*, 118.
- 35 biologists Peter and Rosemary Grant: The Grants' work is memorably described in Jonathan Weiner's *Beak of the Finch*. Work on the new species was reported in 2018, in Lamichaney et al., "Rapid Hybrid Speciation in Darwin's Finches."
- 36 Lewis Terman's decades-long "Genetic Studies of Genius": Beginning in 1921, Terman recruited California children between the ages of 8 and 13 who scored especially well on a battery of tests, especially the Stanford-Binet IQ test that he had himself developed. His aim was to follow these "gifted" children through their lives, examining the ways in which their "genius" flowered. But it turned out that they were not much more apt to display great creative power than any other children. The assumption that IQ and genius go hand in hand was mistaken. The project continues to this day, tracing the lives of subjects now in their nineties but with rather different research goals in mind.
- 37 a summer she spent in Colorado: As related in Jahren's *Lab Girl*, 73–75.
- 37 "You have to believe": Quoted in Aschwanden, "Science Isn't Broken," at <http://fivethirtyeight.com/features/science-isnt-broken/>.
- 38 "Only a person such as myself": From the autobiographical note Schally wrote upon being awarded the Nobel Prize (<https://www.nobelprize.org/prizes/medicine/1977/schally/biographical/>).
- 40 I think that Popper and Kuhn are correct: Were I keeping score, I would give Kuhn extra credit here: he puts more emphasis than Popper on the motivating power of methodological consensus.

## CHAPTER 2: HUMAN FRAILTY

- 42 **by a young Karl Popper:** As related in the previous chapter, the eclipse experiment and other tests of relativity directly inspired Popper's idea of falsification. Thus, not only was the experiment in the Popperian mold; it molded Popper himself.
- 45 **"the logic of the situation does not seem entirely clear":** Campbell is quoted on p. 78 of Earman and Glymour, "Relativity and Eclipses," my principal source on criticisms of the eclipse experiment.

A defense of Eddington's neglect of the Brazilian astrographic plates is mounted by the physicist Daniel Kennefick in "Testing Relativity from the 1919 Eclipse." Kennefick clearly explains how a "change of scale" would create a systematic error, but he does not address the curious fact that Eddington and his coauthors make no attempt to convince their readers that such a change had occurred, rather than there having been a simple loss of focus that would not create any systematic bias in the astrographic measurements. As far as we can tell, Eddington simply chose the explanation for the blurriness of the astrographic's photos that best suited his goals. I will take up the question of Eddington's omission again in Chapters 3 and 7.

Matthew Stanley's "An Expedition to Heal the Wounds of War" is also largely sympathetic to Eddington's treatment of the data and provides much fascinating historical background. Stanley gives a broader perspective in his book *Einstein's War*.

- 45 **"the pursuit of truth":** Quoted by Matthew Stanley, "Expedition to Heal the Wounds of War," 64. Stanley argues that Eddington saw the eclipse expedition as a "religious calling" (p. 59).
- 45 **"the most influential figure in British astronomy":** Earman and Glymour, "Relativity and Eclipses," 71.
- 46 **According to Karl Popper:** There are other ways in which the episode of the eclipse resists a simple Popperian interpretation. The Brazilian telescopes yielded two conflicting measurements of the bending of light, which poses an obvious problem for falsification as a scientific method: no theory can predict both outcomes; thus, every theory will be falsified. In the next chapter, we will see what Popper has to say about this.
- 46 **According to Thomas Kuhn:** Should Eddington's eclipse experiment be regarded as taking place within the Newtonian paradigm or the incipient Einsteinian paradigm? Such questions arise frequently when attempting to read history in Kuhnian terms: science has often failed to unfold in the neat fashion described in Kuhn's *Structure of Scientific Revolutions*. As a consequence, Kuhn continued to refine his conception of the cycle of paradigm-governed science, crisis, and revolution after the publication of his most famous book. Most historians of science, however, while they acknowledge Kuhn's enormous importance, have abandoned the attempt to understand the history of science in terms of a series of successive paradigms for this reason as well as the reasons discussed throughout the present chapter. The role of Kuhn's ideas in contemporary history of science is laid out succinctly in Mario Biagioli's short paper "Productive Illusions."
- 47 **science's biggest names can be seen discarding:** See, respectively, Fisher, "Has Mendel's Work Been Rediscovered?"; Richardson et al., "There Is No Highly Con-

- served Embryonic Stage in the Vertebrates"; Holton, "Subelectrons, Presuppositions, and the Millikan-Ehrenhaft Dispute"; Westfall, "Newton and the Fudge Factor" (the quote is from p. 753). In each case, accusations of impropriety have spurred illuminating debates about the culpability of the scientists and the damage done to science—with some writers arguing for little culpability and less damage—but there is scant doubt that a certain amount of deliberate misrepresentation took place.
- 48 **Eddington's original presentation:** Dyson, Eddington, and Davidson, "Determination of the Deflection of Light."
- 52 **Pasteur and Pouchet had sparred:** This story is told in Collins and Pinch, *The Golem*, which also contains a brief, accessible, and rather unsympathetic account of Eddington's maneuvers.
- 52 **a combative and unfair disputant:** A balanced biography that takes the notebooks into account is Patrice Debré's *Louis Pasteur*.
- 53 **the industry-supported group is considerably more likely:** On soda: Bes-Rastrollo et al., "Financial Conflicts of Interest and Reporting Bias Regarding the Association between Sugar-Sweetened Beverages and Weight Gain." On secondhand smoke: Barnes and Bero, "Why Review Articles on the Health Effects of Passive Smoking Reach Different Conclusions." On drug trials: Cho and Bero, "Quality of Drug Studies Published in Symposium Proceedings." See also Bekelman, Li, and Gross, "Scope and Impact of Financial Conflicts of Interest in Biomedical Research."
- 54 **a young German scientist and explorer:** Mott Greene's *Alfred Wegener* offers a comprehensive treatment of Wegener's life, which I draw on here.
- 57 **we might still be waiting:** The evidence that pointed to seafloor spreading as the mechanism by which continents are moved was uncovered by scientists who were not thinking about drift at all—more reason to think that the last thing science ever should do is to slow down or stop.
- 58 **scientists in the United States:** Naomi Oreskes, in *Rejection of Continental Drift*, surveys the speculations about the mechanism for drift that appeared in and after Wegener's work. Oreskes's explanation of the controversy is somewhat different from mine, although it exemplifies, in its own way, my point about the importance of differing methodological tastes: she explains the US geologists' caution as grounded in a suspicion of grand, theory-driven geology in favor of a bottom-up, inductive, theoretically pluralistic (or even agnostic) approach. I myself interpret the "inductive" stance of the American geologists as comprising, among other things, a demand that each working part of a big, systematic theory be independently evidenced and thus that the drift mechanism postulated by Wegener's theory be not merely possible in principle but be supported by observations that go some way toward demonstrating its existence.
- 59 **"[science] is beautifully self-correcting":** In a 2016 commencement address at Cal Tech; a transcript is posted at <http://www.newyorker.com/news/news-desk/the-mistrust-of-science>.
- 60 **Latour's "knowledge of science was non-existent":** All quotes in this paragraph are from Latour and Woolgar, *Laboratory Life*, 273.
- 60 **"inscription devices":** Latour and Woolgar, *Laboratory Life*, 51.
- 62 **"local tacit negotiations":** Latour and Woolgar, *Laboratory Life*, 152.

- 62 "We were unable to identify": Latour and Woolgar, *Laboratory Life*, 189.
- 63 "The work they were doing": Zimring, *What Science Is and How It Really Works*, 279.
- 63 "The natural world has a small or non-existent role": Collins: in "Stages in the Empirical Programme of Relativism," 3. Aronowitz: in *Science as Power*, 204. "the strongest team": in Patricia Fara, *Science: A Four Thousand Year History*, 257. Brassy subjectivist slogans such as these are collected by Alan Sokal at <https://scientiasalon.wordpress.com/2014/03/26/what-is-science-and-why-should-we-care-part-i/>.
- 64 hopeless, each and every one: I have been principally interested, in this chapter, in aspects of scientific practice that undermine the methodist approaches of Popper and Kuhn equally. Thus, I have not made much of signs that many scientists actively seek to overthrow the prevailing orthodoxy (see, for example, "We Want to Break Physics" at <http://www.bbc.com/news/science-environment-31162725>). Such rebel yells are bad for Kuhn but good for Popper. Likewise, I have not dwelt on cases where scientists unthinkingly echo the orthodoxy—bad for Popper but good for Kuhn.
- 64 science's theoretical as well as its practical success: The question of the relation between science and technology was much discussed in science studies in the 1980s. Opinion eventually settled on what is called the "interactive view," described by, for example, Alexander Keller: "So—has science created technology? The answer must be twofold. One answer is: No, it was not the prime originator. . . . The other is: Yes, modern technology would be impossible without scientific training and comprehension of the nature of things" (in "Has Science Created Technology?," 182). Keller's piece includes an illuminating overview of postwar research on connections between basic science and technological innovation.
- 64 "Science remains": Shapin, *The Scientific Revolution*, 165. Even Harry Collins, whose radical dictum was quoted earlier, is happy to say that scientists are "the foremost experts in the ways of the natural world" (writing with Trevor Pinch in *The Golem*, 142).

### CHAPTER 3: THE ESSENTIAL SUBJECTIVITY OF SCIENCE

- 66 "some kind of lighter fluid": Quoted in David Grann, "Trial by Fire," *New Yorker*, September 7, 2009.
- 67 those who contributed to the case against him: Apparently, the people involved in Willingham's conviction still on the whole believe that he was guilty.
- 73 do the experiment a second time: Popper's requirement is stronger than this: for falsification he requires "corroboration" of a "falsifying hypothesis," which implies the repeated production or observation of the falsifying fact.
- 73 "would not occur again for many years": Dyson, Eddington, and Davidson, "Determination of the Deflection of Light," 293.
- 75 "a creating and directing power": The quotations are taken from Smith and Wise's biography of Kelvin, *Energy and Empire*, 645.
- 75 But the science of Darwinism: Charles Darwin himself suffered a gradual loss of faith. Reflecting about it later in life, he wrote, "Disbelief crept over me at a very slow rate . . . so slow that I felt no distress, and have never since doubted even for a single second that my conclusion was correct" (Darwin, *Autobiography*, 87).
- 76 Kelvin presumed the original temperature: Also important to Kelvin's estimate, and also measured by Forbes, was the temperature gradient, that is, the degree to

which the earth gets hotter as you dig deeper. Forbes was of course only able to estimate this gradient very close to the surface.

- 76 **"much nearer 20 than 40":** Quoted in Dalrymple, *Age of the Earth*, 43.
- 76 **Darwin stood refuted:** Perhaps even more than Darwinism, Kelvin was concerned to refute the "uniformitarian" geology of the mid-nineteenth century, with its appeal to the "inconceivably vast" lengths of time needed to deposit the strata and to build the geological formations to which geologists' eyes were for the first time being opened. By finding beginnings and endings, it seems, Kelvin sought to restore a narrative arc to the unfolding of time, making a place for both creation and redemption. But he did not neglect the impact of his calculations for the hypothesis of evolution by natural selection: his limit on the earth's age, he wrote with evident satisfaction, "seem[ed] sufficient to disprove" Darwin's hypothesis (cited in Burchfield, *Lord Kelvin and the Age of the Earth*, 85).
- 77 **"What you get out":** From Huxley's presidential address to the Geological Society of London in 1869, in which he launched his initial attack on Kelvin's dating. Cited in Burchfield, *Lord Kelvin and the Age of the Earth*, 84.
- 77 **"Natural Philosophy . . . already points":** Quoted by David Lindley, *Degrees Kelvin*, 176.
- 77 **he was relying on assumptions:** Kelvin's assumptions are explored in Dalrymple, *Age of the Earth*, 46-7. An engaging presentation of the importance of convection in particular may be found in England, Molnar, and Richter, "Kelvin, Perry and the Age of the Earth."
- 78 **Huxley was right:** The estimates of the age of the sun were also based on false assumptions. Kelvin and the other estimators, Hermann von Helmholtz and Simon Newcomb, had supposed that the sun's energy was due to gravitational contraction; in fact, it is almost all supplied by the then unknown process of nuclear fusion.
- 79 **only as strong as its weakest link:** A complex chain of reasoning may have a structure that is more sophisticated than a simple sequence of links. At some points, for example, the chain might briefly separate into two strands, each bearing some of the weight, as when a critical assumption is supported by two independent considerations. In these cases, it is not always true that the chain is no stronger than its weakest link. But the more general moral—that reliably estimating the strength of a chain is impossible without reliably estimating the strength of its individual links—does hold true.
- 81 **the solidity assumption:** Kelvin in fact devoted considerable time and energy to arguing for the assumption of solidity: he considered various ways in which a sphere of molten rock—as he supposed the earth once was—might cool, and he concluded that according to any of these stories, the earth would have solidified early in its history. He did his best, then, to extrapolate from contemporary physical knowledge, but generalizing to an entire planet turned out to be, as Huxley and company had surmised, a step too far.
- 82 **an unbreakable circle:** The same circles can turn up even in the absence of big theoretical auxiliary assumptions. One complaint about Eddington's interpretation of the eclipse observations was that, in calculating the light-bending angle implied by the Principe telescope's measurements, he at one point assumed the correctness of Einstein's theory—the same theory that the measurements were supposed to

test. Some sociologists call the circularity that precludes an independent objective test of auxiliary assumptions “the experimenter’s regress.” Philosophers call it (I’m sorry to say) “confirmation holism.”

- 83 **The heart of scientific logic is a human heart:** To more precisely formulate these ideas, philosophers have constructed probabilistic logics to capture scientists’ plausibility rankings and their role in evaluating evidence. Such logical systems differ in various ways, but they all implement to some extent a simple idea: if your chain breaks, suspect the weakest link.

The most influential probabilistic system was first developed by the eighteenth-century clergyman and mathematician Thomas Bayes (1701–1761). Bayes’s approach cannot be wholly correct—it assumes that scientists know all possible theories in advance—but it provides an excellent model of many aspects of scientific inquiry.

In the Bayesian framework, scientists’ plausibility rankings for the things that matter—hypotheses and auxiliary assumptions—are represented by numbers between 0 and 1, varying from person to person. From some simple mathematical facts and an equally simple supposition about the way that scientists take new evidence into account, it is easy to show that the significance of a piece of evidence can vary dramatically, depending on a scientist’s plausibility rankings. Indeed, one and the same piece of evidence may appear either to support or to undermine a theory, given different rankings. The demonstration abstracts away from the flesh-and-blood reasons why scientists differ in their rankings: it treats aesthetic judgments, politically expedient rationalizations, and raw self-deception in exactly the same way. But in so doing it exposes something that all plausibility rankings, whatever their origins, share: the power to foment disagreement as to what the evidence says, a power that consequently frustrates any attempt to formulate an objective rule for weighing evidence. Some further implications of Bayesian logic are discussed in a note to Chapter 5 (“plausibility rankings begin to converge”).

#### CHAPTER 4: THE IRON RULE OF EXPLANATION

- 92 **Perhaps, he suggests:** An alternative explanation posits an invisible substance filling even apparently empty spaces, through which heat could flow in the same way that it flows through more everyday materials. That is the transitional “wave theory” of heat, which supplanted caloric theory in the 1830s but then itself yielded to kinetic theory in the 1840s. Apart from the need to explain heat’s ability to travel through empty space, the wave theory was motivated by the widespread belief (eventually shown to be false) that heat and light are at bottom the same sort of thing.
- 92 **The sun’s heat:** Besides infrared radiation, a good amount of the sun’s heat comes by way of visible light in virtue of a process slightly more complicated than simple absorption. This complication does not affect the following discussion, which is premised on Montague’s assumption that light rays and heat rays are distinct kinds of radiation.
- 92 **These heat rays are not:** As physicists were to discover in the twentieth century, electromagnetic radiation is composed of streams of photons, particles that behave partly in a wavelike, partly in a raylike, manner.

- 95 **If heat rays are like light rays:** Ordinary glass does in fact block some "heat rays" (that is, some frequencies in the infrared spectrum). A black plastic garbage bag, though opaque to visible light, is transparent to infrared radiation.
- 96 **find an experiment or observation:** Sometimes testing turns on an observation or experiment that is not quite so revealing: one hypothesis (or rather, cohort) has an opinion about the outcome, but the other does not. The second hypothesis is, in that case, indifferent to what happens; in effect, the observation tests the first hypothesis while the other stands by, benefiting in a passive way if the first fails the test, like a politician taking advantage of an opponent's scandal.
- 97 **the nub of the scientific method:** As I have formulated it, the iron rule turns on hypotheses' ability to explain. Scientists often say, however, that it is by predictions that theories are tested. Wasn't it predictive differences that distinguished the Newtonian and Einsteinian theories of gravity or, indeed, the caloric and kinetic theories of heat?

Yes it was, but such predictions are typically explanations as well. Einstein's theory not only predicts that light passing the sun will be bent to a certain degree; it also explains why it is bent to precisely that degree. Likewise, Montague's theory of radiation not only predicts that heat will pass through glass without slowing; it explains why that is so. Insofar as this duality of prediction and explanation holds, it hardly makes a difference whether the iron rule is formulated in terms of one or the other.

There are numerous explanations, however, that are not predictions: evolutionary theory, the social sciences, much of geology and economics, and even cosmology explain far more than they predict. Evolutionary biologists can give a rather good explanatory account, for example, of various distinctive physiological features of the human body, but they could never have predicted its form if, impossibly, they were conducting their research 30 million years ago, just as the ape and monkey lineages diverged.

What makes prediction harder than explanation in a case like this is that prediction, but not explanation, requires everything relevant to be known in advance. In explanation, by contrast, you have the many benefits of hindsight. To predict the behavior of a friend or a lover in a sticky situation—that can be a challenge. But in the aftermath, the explanation for what they did is often abundantly clear. Life is like that.

So is the science of life. The biologists of 30 million years ago could not have predicted that modern humans would walk on two legs, because they could not have known for sure either that full bipedalism was developmentally possible in the monkey lineage—that the body plan of humanity's ancestors would allow such a physiological configuration—or that it would be selectively advantageous. From the perspective of now, these uncertainties are eliminated: the possibility and advantages of bipedalism are manifest. Facts discovered after the event go into the explanatory theory like any others, allowing a derivation that would be beyond our reach if what were being explained had not already come to pass.

If the criterion for empirical testing is to regulate the pursuit of historical sciences such as evolutionary theory, then it is explanatory rather than predictive power on which the criterion for empirical testing must be built.

- 98 **empirical inquiry has seen nothing like this:** The one exception I can think of is

the formation of psychoanalytic schools after Freud—Jung, Adler, and the rest. But this was possible precisely because the psychoanalytic tradition came to reject the procedural consensus, allowing matters other than observable evidence into the debate. In this respect, it is closer to ancient natural philosophy, which begat the Stoic and Epicurean schools, than it is to modern psychology: it is an attempt to frame a worldview, not a mere science.

- 99 **the hypothalami of 160,000 pigs**: From Schally's Nobel autobiographical note (<https://www.nobelprize.org/prizes/medicine/1977/schally/biographical/>).
- 99 **"He is the Establishment"**: Quoted in Latour and Woolgar, *Laboratory Life*, 119. Schally is likely referring to S. M. McCann's unsuccessful work on LRF, according to Nicholas Wade in *The Nobel Duel*. Wade summarizes McCann's own diagnosis of his failure: "His prime strategic error, as he sees it, lay in not allocating more of his resources to the LRF chase. Had he devoted more of his budget to buying hypothalami, had he diverted less of [his] stock of LRF to interesting physiological experiments, perhaps the outcome of the LRF race [would] have been different" (p. 222).
- 101 **"I hate the Standard Model"**: For other particle physicists with the same attitude, see "We Want to Break Physics," cited in a note to Chapter 2 ("hopeless, each and every one").
- 103 **my disagreements with Kuhn**: Let me register one further difference between us. For Kuhn, the "rules of science" are more like a way of life: they tell you not only which moves are allowed, but also what counts as a good move and what constitutes "sportsmanlike behavior" (among other things). The iron rule is much closer to the bare regulations of a sport, that is, to what is laid out explicitly in the rulebook. A move can be legal but inadvisable, a sure losing gambit. Likewise, an empirical test can be technically relevant to the argument, yet inconclusive or redundant—as when the same experiment is repeated over and over with the same result.

#### CHAPTER 5: BACONIAN CONVERGENCE

- 105 **Bacon admired the ancient Greek natural philosophers**: Bacon considered early natural philosophers such as Thales and Anaximander to be superior to Aristotle and Plato. To account for the greater fame of the latter, he ventured: "Time (like a river) has brought down to us the lighter, more inflated works and sunk the solid and weightier" (*New Organon*, §1.71).
- 105 **"round in circles for ever"**: This and "a new beginning" from Bacon, *New Organon*, §1.31.
- 107 **"as innocent as any"**: According to John Campbell, *Lives of the Lord Chancellors*, 404.
- 108 **"Every contradictory instance"**: Bacon, *New Organon*, §2.18.
- 108 **"The quiddity of heat"**: Bacon, *New Organon*, §2.20.
- 109 **Bacon's method provides no objective guidance**: Bacon himself encouraged scientists to develop working hypotheses as they go along, "because truth emerges more quickly from error than from confusion" (§2.20). But he did not propose a procedure for choosing between such hypotheses in the absence of fresh evidence. His own "first harvest" theory of heat turned out to be on the right track, so the issue did not arise in his great worked example.

- 110 **plausibility rankings begin to converge:** The Bayesian probabilistic logic, which, as I remarked in a note to Chapter 3 ("The heart of scientific logic is a human heart"), shows that short-term divergence of opinion is inescapable, also shows that under certain circumstances, long-term convergence of opinion is inexorable. The mathematics of the Bayesian system proves, in other words, that as evidence continues to come in, scientists starting out with divergent plausibility rankings will in their opinions come closer and closer to each other and to the truth. As the "under certain circumstances" hedge implies, however, this encouraging conclusion must be qualified in certain ways, corresponding to complications remarked upon in the next note.
- 112 **agreement emerges again and again:** Baconian convergence is not easy, and philosophers have articulated powerful reasons to worry that with respect to some matters, it might not occur at all.

First, in certain domains there might be more than one theory that explains all the observable facts, no matter how many are collected. There would be no Baconian way to choose among these champion explainers.

Second, according to the Baconian ideal, the sheer mass of evidence overwhelms, ultimately, all scientific partisanship and prejudice. But if the evidence is interpreted from a partisan and prejudiced point of view, why be so confident that the evidence will win and partiality will lose? Worse, what if there are false presuppositions about the world hardwired into the human brain? Every scientific thought would be infected by these presuppositions; you might fear, then, that even the most potent dose of empirical evidence could not possibly expunge them from the gray matter—that they will live on in our theories like conceptual parasites as long as the human race persists.

These worries can be quelled, and the resulting discussion is frequently fascinating, probing some of the most profound issues in all of philosophy. To take on such weighty topics would, however, be too much of a burden at this point in the book. Perhaps I should write a second volume? For now, in lieu of that volume, I have offered a simple empirical argument that Baconian convergence is possible: modern science, though young, has achieved it already many times over.

- 112 **Written by Sir Francis Bacon:** Ignatius Donnelly, a late nineteenth-century populist US politician who presciently (as it will soon emerge) maintained that the island of Atlantis once really existed, published *The Great Cryptogram* in 1888, arguing that the works of Shakespeare were in fact written by Francis Bacon. The same thesis was advocated by a number of other nineteenth-century literary adventurers. It has fallen, for good reasons, into disrepute.
- 112 **In a basement in Ohio:** I simplify some of the details of the Michelson-Morley experiment in the main text. The apparatus was slowly rotated, so that all directions of travel relative to the earth's were tested. The beams traveled back and forth a number of times before their arrival time was compared. And the beams were compared by viewing the interference pattern created when they were superimposed.
- 116 **"forces scientists to investigate":** Kuhn, *Structure of Scientific Revolutions*, 25.
- 117 **the first great scientist in history:** Armand Marie Leroi, in *The Lagoon*, writes beautifully about Aristotle's copious observations of and theories about nature, emphasizing their scientific spirit: "He invented the science [of biology]. You could argue that [he] invented science itself" (p. 7).
- 117 **David Lindberg provides a partial list:** In *The Beginnings of Western Science*, 362-4.

## CHAPTER 6: EXPLANATORY ORE

- 123 "no timeless, ahistorical criteria": Dear, *Intelligibility of Nature*, 14.
- 123 **All things, animal, vegetable**: Aristotle notes that there is a difference between inert matter and animals: inert matter is not genuinely self-propelled, or else a dropped coffee cup would not crash witlessly to the floor but would find some way to perpetuate its fall, perhaps ducking out of a window to get closer to its natural nesting place.
- 123 "fell into place": The quotes are excerpts from a longer passage reproduced in Chapter 1.
- 126 **his well-tended beard**: Jonathan Barnes writes of Aristotle, "He was a bit of a dandy, wearing rings on his fingers and cutting his hair fashionably short" (in his *Aristotle*, p. 1).
- 126 "Physics alone cannot explain life": Aristotle makes his argument against the materialists in *Physics*, II.8.
- 127 **It is rather something**: Plants, too, have *psuches*, according to Aristotle, accounting for their functional, adapted forms.
- 127 **the form of the animal in its body**: I have taken this formulation from Leroi, *The Lagoon*, 158. For my purposes, it is an adequate and appealing paraphrase of Aristotle's doctrine that the *psuche* is the "first actuality" of the body (*De Anima*, II.1).
- 129 **the Thirty Years' War would have killed**: On the complicated business of estimating the war's casualties, I have relied on Peter Wilson's *The Thirty Years War*, Chapter 22.
- 130 **he dreamed three times**: The content of the dreams—heavily condensed and highly interpreted here—was recorded by Descartes and related by his early biographer Adrien Baillet; descriptions can be found in any modern biography of Descartes, from Stephen Gaukroger's rich and highly readable *Descartes: An Intellectual Biography* to Richard Watson's charming, discursive, and somewhat eccentric *Cogito, Ergo Sum*.
- 132 **a kind of centrifugal force**: As with centrifugal force in Newtonian physics, Descartes understands this tendency not as a genuine force, but rather as an expression of rectilinear inertia—the tendency of objects to continue moving in a straight line unless something holds them back or gets in their way. Objects moving in a circle, such as anything perched on a rock that orbits the sun, will experience this tendency as a palpable tug pulling them outward and away from their circular path. The planets themselves are subject to the same inertia; it is the invisible matter in which they're embedded that prevents them from making a beeline out of the solar system.
- 132 "nothingness cannot possess any extension": Descartes, *Principles of Philosophy*, §II.18.
- 132 "It is no less impossible": From a letter to Mersenne cited by Garber, *Descartes' Metaphysical Physics*, 131.
- 133 **all other bodily functions**: There is one great exception: conscious thought. Our mental life, believed Descartes, plays out in an immaterial soul that communicates with the body through a small structure in the brain called the pineal gland. However this happens, it cannot be through physical contact—a rather vexing problem

- for a philosopher who has just proved beyond any shadow of personal doubt that all material change is caused by collisions.
- 134 **Aristotle would dismiss Descartes's as hopeless:** Cartesian philosophy would seem to be a prime target for Aristotle's ancient argument against a wholly materialist biology—the argument that the biological world's finely tuned harmony cannot be explained by something as dumb and unruly as impact. Descartes might have attempted to evade this charge by invoking what was for him the religiously orthodox view that God was responsible for bringing biological forms into being through an act of special creation. Aristotle, had he allowed such an event, would still not have been satisfied. Even if the living world were miraculously assembled at a single stroke in all its perfect complexity, Aristotle would contend, that perfection could not last. Like a city abandoned in the jungle, biological structures would slowly deteriorate as small aberrations crept into the mechanisms by which organisms sustain and reproduce themselves. Could God continue to oversee his handiwork, keeping mechanical processes in line and on target to do what's best for an organism? Cartesian mechanics, in that case, would be mere metaphysical theater; the real causation would be God's pulling the strings behind the scenes. Descartes was too pure of a thinker to find such a picture appealing. He insisted that the simple laws of physics were enough to preserve the biological attunement that Aristotle believed could be explained only by *psuche*.
- 135 **"Truth is the offspring of silence":** Newton's words are quoted in Gale Christianson, *Isaac Newton*, 21. Readers looking for a short life of Newton have two superb choices: Christianson's and James Gleick's.
- 136 **"barbaric physics":** Leibniz's vituperative words are in an unpublished essay titled "Anti-Barbarus Physicus," tentatively dated 1710–1716 (in *Philosophical Essays*, 312).
- 137 **how Kuhn spins the history of gravity:** Kuhn, *Structure of Scientific Revolutions*, 103–5.
- 137 **a postscript:** Newton wrote the postscript in part to fend off Leibniz's and others' criticisms of his apparent invocation of action at a distance.
- 137 **"I have not as yet been able":** Newton, *Principia*, 943.
- 137 **frees scientific theory builders to try:** Many historians have remarked on Newton's successful attempt to move the explanatory goalposts, offering varying interpretations of the resulting framework. I. Bernard Cohen, for example, distinguishes a "Newtonian style" (in fact, a thoroughgoing method) in which explanation is shallow in my sense but in addition explicitly mathematical (Cohen, *Newtonian Revolution*).
- 140 **each is warmly welcomed:** Scientists may, of course, assign different plausibility rankings to different kinds of explanations. The iron rule does not demand that scientists treat all explanatory principles equally. But it does demand that they recognize any shallow causal principle's right to participate in scientific argument as a potential explanation.

There are two important differences between denying a principle this right and merely assigning it a low plausibility ranking. The first is that assigning a low ranking makes the evaluation of explanations in science a matter of degree rather than an exercise in censorship; consequently, even the most dimly regarded hypothesis can, if it achieves sufficient explanatory success, come to dominate the discus-

- sion. The second is that assigning rankings brings disputes as to which explanatory principle is best inside the framework of science, where they can be resolved using the empirical power of the knowledge machine.
- 140 **By the time Newton died:** The quoted tributes can be found in Mordechai Feingold, *Newtonian Moment*, 169, 173, 177.
- 142 **“science personified”:** Feingold, *Newtonian Moment*, 148.
- 143 **“Elementary material particles”:** Quoted in Helge Kragh, *Quantum Generations*, 117. Kragh gives a fascinating account of what he calls the “electromagnetic worldview.”
- 145 **“Bohr from out of philosophical smoke clouds”:** Quoted in Kragh, *Quantum Generations*, 213.
- 145 **“Quantum mechanics is certainly imposing”:** In Born and Einstein, *The Born-Einstein Letters*, 91.
- 146 **“met almost no resistance”:** According to Kragh, *Quantum Generations*, 169. On the marginalization of the philosophical aspects of quantum theory in the wider scientific world, see *Quantum Generations*, 211.
- 146 **“mysterious, confusing discipline”:** These and many other such remarks can be found at [https://en.wikiquote.org/wiki/Quantum\\_mechanics](https://en.wikiquote.org/wiki/Quantum_mechanics).
- 146 **let me take you wading:** Here I describe the “non-relativistic” version of the theory that was the subject of the philosophical debates of the 1920s and that is the form of quantum mechanics you would first encounter as an undergraduate physics major today.
- 147 **All that concerns the iron rule:** Because the iron rule looks for the purpose of testing to the observable consequences of causal principles, some thinkers have made the mistake of supposing that science cares only about things that can be directly observed. That is clearly not the case: astronomers care about the interiors of stars, biologists care about the molecular makeup of genomes, and physicists care about the architecture of atoms. Insofar as these unseen entities have divergent causal consequences, their structure can be inferred using the iron rule.
- 147 **the wave function is a complete description:** I am notionally including a specification of the electron’s “spin” in the wave function. Experts will appreciate that the exclusive focus on position in my description of the quantum machinery is a simplification; it is not, I think, a distortion.
- 148 **only three dimensions:** In some versions of what physicists call string theory, the universe has more than three dimensions: 10, 11, or even 26. But these dimensions are “rolled up”; for this and other reasons, they are not suitable for the accommodation of the kind of ether that could provide a substrate for quantum waves. They have other work to do.
- 149 **To sum up, quantum mechanical matter:** This summary skates over numerous subtle interpretative issues. Does an observed particle really acquire a definite position, or does it just act that way? On some understandings of quantum mechanics (the “many worlds” and “many minds” interpretations) it is the latter. Is the wave function really a complete description of a particle’s state? On one understanding of quantum mechanics (Bohmian mechanics), no: particles have definite positions at all times, even when they are exhibiting wavelike behavior. For an accessible and sophisticated introduction to these questions, try David Albert’s *Quantum Mechanics and Experience*.
- 151 **“When confronted with a choice”:** Heilbron, *Electricity in the 17th and 18th Centuries*, 500.

## CHAPTER 7: THE DRIVE FOR OBJECTIVITY

- 152 **Over the walls of a moonlit Spanish cemetery:** As described in Santiago Ramón y Cajal, *Recollections of My Life*, 144–145. The quote is from p. 144.
- 154 **“admirably convenient, since it did away”:** Cajal, *Recollections of My Life*, 336.
- 154 **“artificially distorted and falsified”:** Quoted by by Lorraine Daston and Peter Galison in their presentation of the case in *Objectivity*, 116.
- 154 **“Objectivity was at once”:** Daston and Galison, *Objectivity*, 120.
- 154 **“Thirsting for the objective and the concrete”:** Cajal, *Recollections of My Life*, 145.
- 155 **“exactly prepared according to nature”:** Quoted by Daston and Galison, *Objectivity*, 116.
- 159 **“Thus the results of the expeditions”:** Dyson, Eddington, and Davidson, “Determination of the Deflection of Light,” 332.
- 159 **“diffused and apparently out of focus”:** Dyson, Eddington, and Davidson, “Determination of the Deflection of Light,” 309.
- 159 **“much less weight”:** Dyson, Eddington, and Davidson, “Determination of the Deflection of Light,” 312.
- 160 **“difficult to say”:** Dyson, Eddington, and Davidson, “Determination of the Deflection of Light,” 309.
- 160 **He does nothing of the sort:** Also missing from the paper is an explanation of why the 4-inch telescope’s mirror would not have been affected in the same way as the astrographic’s mirror by the sun’s heat.
- 161 **arguments appearing in official scientific venues:** Sometimes the conclusion is weakened to reflect the thinness of the argument: it is not unusual for a paper to conclude with nothing more than the rather anodyne comment that the observed data is “consistent with” the hypothesis under scrutiny.
- 162 **“There is hardly any difference”:** Feyerabend, *Science in a Free Society*, 82.
- 164 **the singular kind of objectivity achieved by sterilization:** There is a parallel between science’s focus on objectivity in specific official venues and the institution of courts of law, in which arguments in the courtroom are also governed by stringent rules dictating what kinds of considerations may and may not appear. The courts’ restrictions, however, stem more from principles of fairness, such as the US Constitution’s prescription that “in all criminal prosecutions, the accused shall enjoy the right . . . to be confronted with the witnesses against him,” than from a concern with objectivity for its own sake.
- 166 **“vast pile”:** Sprat, *History of the Royal Society of London*, 118.
- 166 **“The Society has reduced its principal observations”:** Sprat, *History of the Royal Society of London*, 115.
- 167 **“We took a slender and very curiously blown cylinder”:** Quoted in Dear, “Totius in Verba,” 153. Dear’s own acute characterization of the passage, and of the house style of the early *Transactions* in general, is from the same page.
- 168 **can be gamed to illuminate the data:** The process of running through many different statistical analyses to squeeze some significant result from a set of observations is called “data dredging” or (referring to a particular class of statistical methods) “*p*-hacking.” You can try out *p*-hacking yourself at <http://fivethirtyeight.com/features/science-isnt-broken/> (Aschwanden, “Science Isn’t Broken”).

- 169 "The particular and endless modifications": Scoresby, *Account of the Arctic Regions*, vol. 1, 426-7.
- 169 During one particularly brutal winter freeze: As described in Glaisher, "On the Severe Weather at the Beginning of the Year 1855," 16-30.
- 171 "the old-school version of Photoshop": Libbrecht's comparison to Photoshop and his snowflake statistics are from Pilcher, "No Great Flakes," 71.
- 172 even the camera has a point of view: Many further fascinating aspects of the changing notion of objectivity in scientific imagery, including both the Cajal-Golgi dispute and the case of snowflakes, are described in Daston and Galison's book *Objectivity* and in the literature on which it draws.

#### CHAPTER 8: THE SUPREMACY OF OBSERVATION

- 173 "Experiment is the sole judge of scientific truth": From the opening pages of Feynman's *Lectures on Physics*, Herschel's *Preliminary Discourse on the Study of Natural Philosophy* (p. 80), Medawar's *Induction and Intuition in Scientific Thought* (p. 42), and Hawking and Roger Penrose's *Nature of Space and Time* (p. 121).
- 174 Whewell's "temper will never be good!": Quoted in Laura Snyder, *Philosophical Breakfast Club*, 209. Snyder's book provides an excellent introduction to Whewell's life and accomplishments.
- 174 "In early days": From Leslie Stephen's entry on Whewell in *The Dictionary of National Biography*, 460.
- 176 "The species of plants and animals": Whewell, *History of the Inductive Sciences*, vol. III, 569.
- 176 "other powers": Whewell, *History of the Inductive Sciences*, vol. III, 582.
- 177 would not emerge for another 20 years: Arriving sooner, in 1844, would be the Scottish journalist Robert Chambers's anonymously published *Vestiges of the Natural History of Creation*, a book that told an evolutionary story in which simpler organisms were transmuted into more complex organisms, ending with the evolution of the human species. Unlike Darwin, Chambers attributed it all to a Creator: evolution was in accordance with "a natural principle flowing from [God's] mind" (p. 154). He was in this respect a man of his time, far closer in his thinking to Whewell than to Darwin.
- 177 "every advance in our knowledge": From Whewell's Bridgewater Treatise, *Astronomy and General Physics Considered with Reference to Natural Theology*, vi, 252-3.
- 178 "must never be allowed": Whewell, *History of the Inductive Sciences*, vol. III, 583.
- 178 "the ordinary evidence of science": Whewell, *History of the Inductive Sciences*, vol. III, 582.
- 178 theology was able to fill these blanks: Whewell did prevaricate a little, maintaining that on theological grounds alone it would be difficult to predict "the detail of all events in the history of man, or of the skies, or of the earth," or at least that the attempt to do so would not be "immune from error" (*History of the Inductive Sciences*, vol. III, 585). But this proviso, to someone with Whewell's beliefs, hardly precluded theology's having something relevant and interesting to say about the creation of species: even if it did not supply "the detail of all events," it might have contributed considerably to humanity's understanding of their broad outlines.
- 179 He repudiated the project: Thomas Burnet's *Sacred Theory of the Earth*, published in the late seventeenth century, gives a sense of what such a project might look like.

- Burnet's subject matter is, like Whewell's, the geological history of the earth. His argument effortlessly and cogently mingles physics and scriptural interpretation, both his own and that of earlier Christian thinkers. The method looks strange to intellects like ours, habituated to the ways of modern science, but it makes perfect sense if you suppose, as Burnet did, that sacred texts tell us something about the history of the world. Burnet was not a literalist; he uses common sense, his knowledge of natural processes such as the flow of rivers, and biblical scholarship to temper his application of the texts (see Figure 3.3). A presentation and appreciation of Burnet's thinking may be found in Stephen Jay Gould's *Time's Arrow; Time's Cycle*.
- 179 "You have no idea": Quoted in Snyder, *Philosophical Breakfast Club*, 367-8.
- 182 "that reason, whether finite or infinite": Whewell, *History of the Inductive Sciences*, vol. III, 586.
- 183 "Concerning Magnesia or the Green Lion": The excerpts from Newton's notebooks in this chapter are taken from Richard Westfall's biography of Newton, *Never at Rest*, 292, 367-8.
- 185 "well over a million words": According to Westfall, *Never at Rest*, 290.
- 185 "to liberate the spirit or active virtue": An interpretation suggested by Westfall, *Never at Rest*, 364.
- 186 "The vital agent": Quoted in Westfall, *Never at Rest*, 304.
- 187 a belief in the *prisca sapientia*: Most notable among those emphasizing Newton's commitment to the *prisca sapientia* are J. E. McGuire and P. M. Rattansi ("Newton and the 'Pipes of Pan'"), Betty Jo Dobbs, who published the first full-length scholarly study of Newton's alchemy in 1975 (*Foundations of Newton's Alchemy*), and Frank Manuel (*Religion of Isaac Newton*).
- 187 "the net": Some of Newton's references to the legend are compiled by Westfall, *Never at Rest*, 296.
- 187 Francis Bacon, decades earlier, warned: In his *New Organon*, §1.65.
- 188 "the last of the magicians": Keynes, "Newton, the Man," 27.
- 188 His intellect operated: There are no absolutes in psychology, not even Newton's; thus, it is possible to find incipient signs of integration in his work. He attempted to fuse his alchemy with the atomist conception of matter; his physics borrows the idea of absolute space from his philosophy (although with an additional empirical justification); his theory of gases borrows particles from his work on light and borrows the forces between them (albeit repulsive) from his work on gravity.
- Some historians have made a case for hidden connections between Newton's various inquiries. David Castillejo used numerological arguments to claim that Newton's thought was "ruthlessly interlocked"; he saw a correspondence, for example, between the four sides of Newtonian light rays and the four walls of another of Newton's interests, Solomon's temple. But contemporary historians have by and large conceded the obvious: "There is surprisingly little cross-referencing of themes from one area of Newton's endeavors to another," writes George Smith ("Isaac Newton"). Sarah Dry offers an overview of recent Newton interpretation in *The Newton Papers* (on Castillejo, see pp. 200-201).
- 192 Newton gave his successors: Reading Newton's prescription carefully, you can see in addition the germ of the iron rule's other negative injunction, its prohibition on anything subjective. Hypotheses, Newton holds, must be established by *deducing* them from the phenomena, a formulation that suggests an appeal to objective laws

of logic alone. In a few words, then, Newton encapsulates and entrusts to posterity the entirety of the iron rule's negative side.

For the same reason that contemporary philosophers of science believe that scientific reasoning is essentially subjective, they doubt that Newton or any other scientist has ever successfully deduced a hypothesis from observable phenomena alone: plausibility rankings are always part of the mix. Newton's formulation therefore serves more as an exhortation toward objectivity than as an accurate summary of his method. As I concluded in Chapter 7, however, an attempt to make scientific argument objective—to "sterilize" the subjectivity away—can be highly effective even when not wholly successful.

- 192 "It is no less of a problem": Bacon, *New Organon*, §66.
- 193 Bacon's rationale for shallow explanation: Bacon is famous for remarking (without quite using this pithy expression) that knowledge is power. In making the case for shallow explanation, he seems to advocate the coarser doctrine that knowledge is valuable only insofar as it is power. Perhaps this is what William Harvey, who discovered the circulation of blood and was for a time Bacon's physician, was insinuating when he said that Bacon "writes philosophy like a Lord Chancellor."
- 193 "To keep my judgement": From the preface to Boyle's *Some Specimens of an Attempt to Make Chymical Experiments Useful*, 355. The preface was most likely written around 1660.
- 194 modern historians doubt: Boas, *Robert Boyle and Seventeenth-Century Chemistry*, 26–28.
- 194 He needed no direction: We know that Newton read Boyle, but as far as we know he never read Bacon. Nor may he have read Galileo's most Newtonian work, the *Two New Sciences* (Westfall, *Never at Rest*, 89; Cohen "A Guide to Newton's *Principia*," in Cohen and Whitman's translation of the *Principia*, 146).

#### CHAPTER 9: SCIENCE'S STRATEGIC IRRATIONALITY

- 201 "Credit must be given": Aristotle, *On the Generation of Animals*, III.10, 760b29–30, translated by Arthur Platt, in *Complete Works of Aristotle*.
- 201 It makes for a fascinating story: Readers interested in learning more about the causes of the Scientific Revolution will enjoy H. Floris Cohen's *Rise of Modern Science Explained* or David Wootton's *Invention of Science*. Cohen and Wootton ask, like me, "What exactly was it that enabled seventeenth- and eighteenth-century science to make progress in a way that previous systems of knowledge could not?" (Wootton's words, p. 4); unlike me, they present their answers in the form of histories of the origins of modern science that discuss the role of a wide variety of historical factors. For an argument that the Scientific Revolution happened when it did as a matter of chance, read J. D. Trout's provocative *Wondrous Truths*.
- 204 "Their explanation of the phenomena": Aristotle, *On the Heavens*, III.7, 306a, translated by J. L. Stocks, in *Complete Works of Aristotle*.
- 205 Augustine, Avicenna, Averroes, and Aquinas: Augustine was a fourth-century Roman theologian and philosopher; Avicenna (980–1071) and Averroes (1126–1198) were Islamic philosophers working in Persia and Spain, respectively; Aquinas (1225–1274) was an Italian theologian, philosopher, and monk.
- 207 "The flood-gates of infidelity": In Romanes's anonymously published *Candid Examination of Theism*, 51–52.

- 207 perhaps a third of American scientists believe in God: This statistic is drawn from a survey by the Pew Research Center for the People & the Press conducted in 2009 (<https://www.pewforum.org/2009/11/05/scientists-and-belief/>). According to the same survey, about 40 percent of scientists say they do not believe in God or a higher power. These numbers seem not to have changed much in 100 years.
- 207 “non-overlapping magisteria”: Gould writes about this notion in *Rocks of Ages*.
- 207 “Shut up and calculate”: In the rather conflicted words of the thoughtful physicist David Mermin, “What Is Wrong with This Pillow?,” 9.
- 208 “I know of no one”: Weinberg, *Dreams of a Final Theory*, 168–9. Is philosophy really so useless to science? In fact, it has plenty to offer scientists thinking about the meaning of quantum mechanics, as Weinberg sometimes does himself (<https://www.nybooks.com/articles/2017/01/19/trouble-with-quantummechanics/>). But there is no doubt, as I said at the beginning of this chapter, that philosophical reasoning has turned out to be far less useful in empirical inquiry than natural philosophers such as Aristotle once supposed. The reason, above all, is the Tychonic nature of our world, which offers clues that must be won not by deep thought, but by unstinting observation.

## CHAPTER 10: THE WAR AGAINST BEAUTY

- 212 “He looked on the whole universe”: Keynes, “Newton, the Man,” 29.
- 215 the classification of birds: The diagrams in Figures 10.4 and 10.5 are based on those in Vigers, “Observations on the Natural Affinities,” 468, 509.
- 216 A group shared “affinities”: As well as affinities, according to Macleay, groups were related by “analogies” that connected groups occupying the same position, relative to the center, on different circles.
- 216 new taxa with the corresponding affinities: In this connection I can’t resist mentioning Aristotle’s attempt to use the rule of four to predict the existence of as yet unobserved creatures. He reasons that three broad classes of animals correspond to three of the four elements: “Plants may be assigned to the land [that is, earth], the aquatic animals to water, the land animals to air.” There must be a fourth class of animals, then, that corresponds to the fourth element, fire. Why are they nowhere to be found? In a stroke of exquisite biological lunacy, Aristotle suggests that they are living on the moon. (*On the Generation of Animals*, III.11, 761b, translated by Arthur Platt, in *Complete Works of Aristotle*.)
- 217 life has the grand design: The nested quinarian structure is not a true fractal, because the embedding does not go on forever but rather bottoms out at the species level—although Macleay came close to imagining a continuum of species in which infinite nesting might be possible, writing, “If we knew *all* the species of the creation, their number would be infinite, or in other words, . . . they would pass into each other by infinitely small differences” (*Illustrations of the Annulosa of South Africa*, 8n).
- 217 “Nature appeared to me to have branched out”: Macleay, *Horae Entomologicae*, 170.
- 218 One such follower: Darwin’s flirtation with quinarianism is described in Dov Ospovat, *Development of Darwin’s Theory*, 101–13.
- 219 “to study Nature simply as she exists”: Strickland, “On the True Method of Discovering the Natural System in Zoology and Botany,” 192.
- 221 “I know that in the study of material things”: Thompson, *On Growth and Form*, 326.

- 222 "It accounts, by one single integral transformation": Thompson, *On Growth and Form*, 300.
- 223 "a comprehensive 'law of growth'": Thompson, *On Growth and Form*, 275.
- 226 his high regard for beauty and form: In touting the importance of beauty, did Thompson violate the iron rule? Like many of the most creative scientific thinkers, he bent it to near breaking point but then relented and followed its prescription. A distinction must be made between a scientist's acknowledging the role of beauty in the generation of their ideas, on the one hand, and using considerations of beauty to argue for their ideas, on the other. Thompson's rhetoric comes close to the latter, which would contravene the iron rule, but a close inspection of his argument reveals that it turns principally on the ability of certain hypotheses to explain certain observations—thus, the "law of growth" is "proved" by its ability to explain the simple geometrical relations that hold between body plans. Thompson certainly hopes that the reader will see the aesthetic appeal of his ideas—no question of that!—but like every scientist laboring under the iron rule's dominion, he knows that he ought to show rather than to tell.
- 227 "It is more important to have beauty": In Dirac's 1963 essay "Evolution of the Physicist's Picture of Nature," p. 47. Dirac used Schrödinger's Nobel Prize-winning work on quantum mechanics as an example of his precept; he might equally well have cited his own.
- 227 "The only physical theories which we are willing to accept": This famous formulation appears in Wigner's equally famous paper "The Unreasonable Effectiveness of Mathematics in the Natural Sciences." I haven't been able to find an independent source for the words Wigner attributes to Einstein; he may have intended them only as a paraphrase of Einstein's well-known regard for a theory's aesthetic merits.
- 227 You needn't look far to find similar sentiments: Chandrasekhar, *Truth and Beauty*; Deutsch, *Beginning of Infinity*, Chapter 14; Wilczek, *Beautiful Question*. Sabine Hossenfelder voices a dissenting view in *Lost in Math*.
- 232 two new xi particles: Note the additional star that distinguishes these xi particles from those in the octet pictured in Figure 10.11. The difference is in the particles' "spin": the starred xis have spin  $3/2$ , whereas the unstarred xis have spin  $1/2$ .
- 233 It was exactly what the iron rule demanded: Gell-Mann's scheme also implied the existence of another particle, the eta, just as experimenters were beginning to see evidence for it in their data.
- 233 Murray Gell-Mann had secured his Nobel Prize: The prize was awarded in 1969. Along with the Nobel's exclusivity come invidious distinctions. Each of Gell-Mann's great breakthroughs had been made independently and at the same time by another scientist: Kazuhiko Nishijima also discovered strangeness; Yuval Ne'eman, the eightfold way; George Zweig, quarks. No one, however, would dispute that Gell-Mann was a deserving winner.
- 234 "a chief criterion for the selection of the correct hypothesis": Quoted in George Johnson's biography of Gell-Mann, *Strange Beauty*, 239.
- 234 Yet he made no appeal: Gell-Mann's 1962 technical paper on the eightfold way characterizes the scheme in passing as "appealing," but the appearance of that one word is as close as Gell-Mann comes to making an aesthetic case for his theory. He spends several pages discussing possible empirical tests of his ideas.
- 235 "make choices and exercise judgments": B. Greene, *Elegant Universe*, 166–7.

- 235 “aesthetic judgments do not arbitrate scientific discourse”: B. Greene, *Elegant Universe*, 166.
- 236 **a scorebook should be maintained**: This is the advice offered by the philosopher of science James McAllister in his book *Beauty and Revolution in Science*.
- 237 **That is illogical, unreasonable, irrational**: Technically, what the iron rule does wrong from a logical point of view is to violate what philosophers call the “principle of total evidence,” a rule of rationality that requires that in making a case for a view, you must (insofar as is practically possible) take every relevant consideration into account. In scientific reasoning, aesthetic reasons are relevant, but the iron rule ignores them.

I must emphasize that the iron rule does not force individuals to contravene the principle of total evidence in their private scientific reasoning. Many take full advantage of this latitude, incorporating into their evaluation of theories whatever kinds of nonempirical reasons—aesthetic, philosophical, religious—they take to be important. Indeed, some of the most thoughtful people I know are psychologists, physicists, linguists, biologists. It is not scientists’ thinking, but science as a social process of cooperative inquiry, as a mode of intellectual engagement, as a set of rules for conducting a public argument, that disregards the rules of logic.

#### CHAPTER 11: THE ADVENT OF SCIENCE

- 242 “I realized that it was necessary”: Descartes, *Meditations I* (published in 1641).
- 243 “A new beginning has to be made”: Bacon, *New Organon*, §1.31; also quoted in Chapter 5.
- 243 **without precedent in human history**: Fifth- and fourth-century BCE Athens is perhaps the seventeenth century’s only serious rival.
- 243 **such tremendous variety**: Many historians have attempted to explain the early modern European penchant for novelty. Was it enabled by the world’s first mass medium, the newly invented movable-type printing press? Was it inspired by the discovery of the New World and the growth of international trade? Was it swept along by the economic and demographic recovery from the devastation of the Black Death? I won’t take a stand on this question; it’s enough that among many other things it happened to throw up a rather thoroughgoing empiricism.
- 243 **the explanation has barely begun**: To suppose that the “right” ideas, once someone goes to the trouble to have them, will inevitably triumph over the rest, as though they are taken up on the shoulders of a band of heroes and borne toward the future along a rose-petaled path, is to indulge in the fallacy that the scholar Herbert Butterfield termed “whig history.”
- 244 **Boyle wrote a great deal**: Boas, *Robert Boyle and Seventeenth-Century Chemistry*, 75–78. “little bodies”: quoted on p. 82.
- 246 **“The terms Protestant and Catholic”**: Wedgwood, *Thirty Years War*, 373.
- 246 **“It was not that faith”**: Wedgwood, *Thirty Years War*, 372.
- 246 **For civic purposes, what mattered**: Although Britain was not directly involved in the Thirty Years’ War, much the same effect was realized by the English Civil War of 1642–1651 and its aftermath.
- 247 **separation of political and religious identity**: Louis XIV attempted, for example, to reimpose Catholicism on all of France in 1685.

- 247 "The laws of God & the laws of man": Newton, "Seven Statements on Religion."
- 247 a permanent bisection: The German political philosopher and jurist Samuel von Pufendorf, born among the battlefields of the Thirty Years' War in Saxony in 1632, wrote memorably of an individual's different "moral personae"—as citizen, shopkeeper, spouse—each governed by a distinct code. For the sake of peace, it was imperative that these codes not conflict. They must be confined to separate areas of life, or, where their jurisdictions overlapped, there must be a clear, universally agreed on order of precedence among them. (Pufendorf's moral agents included not only individuals but also associations of various kinds; religions entered into his system as corporate bodies operating within and across states.) In the seventeenth century, Pufendorf's influence was immense; then, as his thought lost its pertinence in an increasingly liberal Europe, his reputation waned.
- 250 fraudulent emendations: In the fourth century, the Church Father Athanasius led a campaign to establish the doctrine of the trinity as orthodoxy within the Catholic Church. Newton conjectured that certain parts of the New Testament—in particular, the first letter of John and the letter to Timothy—were later deliberately altered to favor the doctrine, for which he discerned no support in the earliest Christian writings.
- 250 "branded a moral leper": In the words of Newton's biographer Richard Westfall. The story is related in Westfall's *Never at Rest*, 330–34.
- 251 a conflict that arose repeatedly: The most famous case is that of Galileo, convicted of heresy by the Catholic Church in 1633. Galileo did his best to maintain that he neither held nor expressed the view that the earth orbited the sun, nor any other proscribed opinions, but the Inquisition was not ready to make compromises of the sort that later saved Newton's career. Rather than taking Galileo at his word, the inquisitors insisted on looking into his heart—where they discerned, quite accurately, his true beliefs.
- 251 "Do not befriend kings": Al-Nuwayrī, *Ultimate Ambition in the Arts of Erudition*, 96.
- 251 The alternative—perpetual religious conflict: According to the seventeenth century's great genius of political philosophy, Thomas Hobbes, the most common cause of civil war is the difficulty of "obeying at once both God and Man." War has to be avoided at all costs; consequently, Hobbes maintains, even when the monarch is, from the subject's point of view, an "infidel," the subject must obey the law—if necessary conforming publicly to the rites of a state religion that they consider to be corrupt or evil. God, he continues somewhat optimistically, cares only for what lies on the inside: "And for their faith, it is internal and invisible; they . . . need not put themselves into danger for it." (Quotes from Hobbes, *Leviathan*, III.43.)

#### CHAPTER 12: BUILDING THE SCIENTIFIC MIND

- 255 "The average person cannot imagine": Jahren, *Lab Girl*, 54.
- 255 "Every feature of every hole": Jahren, *Lab Girl*, 54–55.
- 256 "indefatigable persistence": Cajal, *Recollections of My Life*, 278.
- 256 "We would not accept": Weinberg, *Dreams of a Final Theory*, 165.
- 258 one of Thomas Kuhn's more controversial papers: Kuhn, in "Function of Dogma in Scientific Research," argues that it is on the whole advantageous to teach the doctrines of the prevailing paradigm to young scientists uncritically.
- 260 "Philosophy is dead": Hawking and Mlodinow, *Grand Design*, 5.

- 261 "My concern here": The interview with Tyson is available at <https://id10t.com/podcast/episode-489-neil-degrasse-tyson-returns-again/>.
- 261 "Philosophy is a field": Krauss's interview can be read at <http://www.theatlantic.com/technology/archive/2012/04/has-physics-made-philosophy-and-religion-obsolete/256203/>.
- 261 "It's shocking that such brilliant scientists": Olivia Goldhill, "Why Are So Many Smart People Such Idiots about Philosophy?," *Quartz*, <http://qz.com/627989/why-are-so-many-smart-people-such-idiots-about-philosophy/>.
- 262 "Philosophers' historic failure": Dawkins's tweet can be read at <https://twitter.com/richarddawkins/status/433519270102708224>.
- 263 "Would a leading North American journal": Quotes are from Alan Sokal, "A Physicist Experiments with Cultural Studies," originally published in the journal *Lingua Franca*. This article and many related resources can be found on Sokal's website at <https://physics.nyu.edu/faculty/sokal/>.
- 263 "Tell most scientists about the 'science wars'": Gould, *The Hedgehog, the Fox, and the Magister's Pox*, 101-2.
- 264 "So many scientists are narrow, foolish people": Wilson, *Consilience*, 62; it is narrowness rather than foolishness that I emphasize here. For similar thoughts, see *Consilience*, 42, and Ziman, *Real Science*, 161.
- 264 "A good commander": Tolstoy, *War and Peace*, 644.
- 264 It seems apt: Schally's comparison is recorded by Latour and Woolgar, *Laboratory Life*, 130.
- 265 These thinkers: I hope I have not omitted any friends or important reviewers.
- 267 "Resolve to abide": Lawrence, *Studies in Classic American Literature*, 27.
- 267 "To be nobody-but-yourself": Cummings, "A Poet's Advice to Students," 13.
- 267 "In this ever-changing society": Schultz and Yang, *Pour Your Heart Into It*, 248.

## CHAPTER 13: SCIENCE AND HUMANISM

- 269 "Let us be driven": Pico della Mirandola, *Oration on the Dignity of Man*, 26.
- 272 what is found beyond the golden gate: The opposition between the two gates stands at the heart of Proust's great novel *In Search of Lost Time*, from which I have stolen these words (taken from the second volume, adapting the Moncrieff/Kilmartin/Enright translation, p. 377).
- 274 "the standard schoolbook": According to H. O. Taylor, *Classical Heritage of the Middle Ages*, 50. Says John Sandys: "In the earlier Middle Ages it was the principal, often the only, textbook used in schools, and it exercised a considerable influence on education and on literary taste" (*Short History of Classical Scholarship*, 68).
- 274 The bridegroom Mercury stands for eloquence: The interpretation offered here—with Mercury representing the three humanistic liberal arts and Philology the four scientific arts—was standard throughout the Middle Ages and is also thought by modern scholars to be what Martianus intended.
- 275 "If the heuristic and analytic power of science": Wilson, *Meaning of Human Existence*, 187. Wilson asserts two pages earlier that it is an "archaic misconception" to suppose that "the farther apart [the sciences and the humanities] are kept, the better" (p. 185).

CHAPTER 14: CARE AND MAINTENANCE  
OF THE KNOWLEDGE MACHINE

- 279 **rising sea levels may have forced:** According to Kulp and Strauss, "New Elevation Data Triple Estimates of Global Vulnerability."
- 280 **the question of agenda setting:** To set science's priorities sensibly, we must balance three demands. First, we need science to address our most pressing needs. That said, we must not neglect more fundamental research that will provide a basis for attending to future needs whose nature is as yet only dimly perceived. And finally, even pure knowledge has its value; we shouldn't neglect research whose insights into the workings of the world will make our lives, assuming that we manage to save them, intellectually richer.

Some writers have suggested that citizen committees should have a say in determining the direction of scientific research: Sheila Jasanoff, in "Transparency in Public Science," and Stephen Turner, in *Liberal Democracy 3.0*, are two. The philosopher Philip Kitcher, in *Science in a Democratic Society*, is also favorably disposed, at least in principle. I myself believe that science's internal system of incentives renders it far more sensitive to society's priorities than might be supposed. It could almost be left to make up its own mind about what matters. But as I have said, that topic must wait until another time.

- 282 **"investigate some part of nature":** Kuhn, *Structure of Scientific Revolutions*, 25, cited earlier in Chapter 5.
- 282 **A Kuhnian program of science education:** As outlined in Kuhn's "Function of Dogma in Scientific Research, cited in Chapter 12.
- 284 **detectors the size of the planet Jupiter:** These are back-of-the-envelope estimates mentioned by many commentators, for example, Sabine Hossenfelder in *Lost in Math*, 178. For a more systematic exposition of the obstacles to testing string theory, you might look at Lee Smolin's *Trouble with Physics*.
- 284 **One suggested revision:** Physicists have not on the whole phrased their amendments in terms of what is allowed in the "official channels of scientific communication," but that seems to me to be the best interpretation of what they have in mind. The philosopher Richard Dawid makes a case along these lines—invoking the idea, mooted at the end of Chapter 10, that we can learn which kinds of explanatory elegance are signs of truth—in *String Theory and the Scientific Method*.
- 284 **"post-empirical physics":** Another amendment to the iron rule would allow string theory to accrue scientific legitimacy by providing explanations of the values of the physical constants—which the Standard Model treats as brute posits—in a way that departs from the canon of shallow causal explanation, by appeal to what is called an "anthropic principle." Anthropic explanations invoke the existence, in our universe, of intelligent observers, remarking that we should expect to see only physical constants that would allow complex life-forms like ourselves to evolve. Scientists and philosophers argue about whether such an aperçu genuinely helps to account for the physical constants having the (approximate) values that they do. What's clear is that anthropic derivations are not explanations of the shallow causal sort allowed by the iron rule: they invoke a fact, the presence of watchful intellects, that is causally irrelevant to the values of the constants. Thus, even if string theory, together with the anthropic principle, gives us reason to expect certain values, that

- prediction or explanation (if it is such) does not, by the lights of the iron rule, constitute the basis for a legitimate empirical test.
- 285 "It will follow orders": Collins and Pinch, *The Golem*, 1.
- 286 "bumbling giant": Collins and Pinch, *The Golem*, 2.
- 288 they assign confidence levels to hypotheses: These terms have precisely specified meanings. A hypothesis endorsed with very high confidence is supposed to have a 9 out of 10 chance of proving correct. A very likely event is supposed to occur with a probability of between 90 and 95 percent. The two scales are combined; thus, the IPCC can state "with high confidence" that a certain event is "more likely than not."
- 288 the IPCC aims to use a range of rankings: The IPCC's "medium confidence" and "more likely than not," then, do not entirely reflect the variation in opinion inherent in the full range of plausibility rankings across the scientific community. "Medium confidence," for example, is compatible with the existence of a substantial minority of scientists who vehemently disagree. An assessment that reflected the complete span of scientific opinion would on many important questions be so indeterminate as to be practically useless.
- 289 "if we care about the future": In Schneider's illuminating discussion of the IPCC's efforts to codify subjectivity, "Confidence, Consensus and the Uncertainty Cops," 434.
- 290 "I had always felt so unable": In a letter from Galileo to Fortunio Liceti, quoted in Frova and Marenzana, *Thus Spoke Galileo*, 414.

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