Scientific Method in Brief

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A brief history of truth

This chapter's history of the conceptions of truth covers 23 centuries in about as many pages. Such extreme brevity allows only four stops, each separated by several centuries: Aristotle around 350 BC, Augustine around AD 400, several scholars in the fledgling medieval universities of Paris and Oxford in the 1200s, and philosopher-scientists of the past several centuries until 1960. Subsequent developments are deferred to the next chapter. This history focuses specifically on truth about the physical world, that is, scientific truth.

For many scientists, their research frontiers are moving so rapidly that most relevant work comes from the past several years. However, this book's topic of scientific method is different from routine scientific research in having a far greater debt to history and benefit from history. Concepts of truth, objectivity, rationality, and method have been around for quite some time. Consequently, great minds from earlier times still offer us diverse perspectives and penetrating insights that can significantly improve our chances of arriving at rich and productive solutions. Also, current thinking and debates about scientific method can be better understood in the light of science's intellectual history.

The most elemental question

The most elemental question about scientific method concerns identifying its basic components: What inputs are required for us humans to reach true conclusions about the physical world? In other words, what must go in so that scientific conclusions can come out? After resolving that initial question, subsequent questions then concern how to secure and optimize these inputs.

The history of attempts to answer this elemental question can be comprehended better by alerting readers from the outset to this chapter's overarching theme. This theme is the subtle and indecisive struggle over the centuries among rationalism, empiricism, and skepticism, caused by an underlying confusion about how to integrate science's logic, evidence, and presuppositions.

Inputs Emphasized by Various Schools and Scholars

Inputs	**Schools and Scholars**
Logic/Reason	Rationalists *Aristotle (ideal), René Descartes, Gottfried Leibniz*
Evidence	Empiricists *Aristotle (actual), John Locke, George Berkeley*
Presuppositions (worried)	Skeptics *Pyrrho of Elis, Sextus Empiricus, David Hume*
Presuppositions (confident)	Mainstream Scholars *Albertus Magnus, Isaac Newton, Thomas Reid*
Logic + Evidence	Logical Empiricists of 1920–1960 *Rudolf Carnap, C. G. Hempel, W. V. Quine*

Presuppositions (confident version) + Evidence + Logic = PEL model in Gauch 2002, with precedents from Albertus Magnus, Robert Grosseteste, and Isaac Newton.

Figure 3.1 Inputs required to support scientific conclusions. Historically, various schools have emphasized different inputs. Logic or reason was emphasized by rationalists, whereas evidence or experience was emphasized by empiricists. Aristotle expressed both an ideal science that aligned with rationalism and an actual science that aligned with empiricism. Presuppositions have been formulated in two quite different versions: a worried version by skeptics and a confident version by mainstream scholars. Logic and evidence were combined by logical empiricists. All three inputs – presuppositions, evidence, and logic – are integrated in the PEL model.

Figure 3.1 lists the inputs emphasized by various schools and scholars. The rationalists expected logic or reason to generate scientific truth. By contrast, the empiricists saw evidence or experience as the touchstone of knowledge and truth. And the skeptics were so worried about science's presuppositions of a real and comprehensible world that they despaired of offering any truth claims, although mainstream scholars advocated a confident version of science's presuppositions. As troubles mounted over the centuries for both rationalism and empiricism, in part because of skeptical attacks, the logical empiricists realized that neither reason nor evidence is adequate separately, so their innovation was a scientific method that combined reason and evidence. But after only several decades, their short-lived project also encountered insurmountable troubles.

The resolution that I proposed in 2002 in my text, *Scientific Method in Practice*, reflects the scientific method of philosopher-scientists such as Albertus Magnus, Robert Grosseteste, and Isaac Newton. Presuppositions, evidence, and logic constitute the three inputs needed to support scientific conclusions. No subset of these three inputs is functional, but rather the combination of all three works.

The details that follow in this and subsequent chapters will make more sense for those readers who grasp two things at this point. First, the most elemental question about scientific method is: What inputs must go in so that scientific conclusions can come out? Second, a satisfactory account of scientific method that answers this question and supports mainstream science will necessarily involve securing and optimizing science's presuppositions, evidence, and logic.

Aristotle

Aristotle (384–322 BC) was enormously important in science's early development. He was a student of Plato (*c.* 429–347 BC), who was a student of Socrates (*c.* 470–399 BC), and he became the tutor of Alexander the Great. Aristotle established a school of philosophy called the Lyceum in Athens, Greece. He wrote more than 150 treatises, of which about 30 have survived.

Aristotle defined truth by the one and only definition that fits common sense and benefits science and technology: the correspondence concept of truth. A statement is true if it corresponds with reality; otherwise, it is false. This definition of truth is obvious and easy, despite the temptation to think that a philosophically respectable definition must be difficult, mysterious, and elusive. As Adler (1978:151) said, "The question 'What is truth?' is not a difficult question to answer. After you understand what truth is, the difficult question, as we shall see, is: How can we tell whether a particular statement is true or false?"

Aristotle had a deductivist vision of scientific method, at least for a mature or ideal science (Losee 2001:4–13). The implicit golden standard behind that vision was geometry. Ancient philosophers were quite taken with geometry's clear thinking and definitive proofs. Consequently, geometry became the standard of success against which all other kinds of knowledge were judged.

Naturally, despite that ideal of deductive certainty, Aristotle's actual method in the natural sciences featured careful observations of stars, plants, animals, and other objects, as well as inductive generalizations from the data. The axioms that seemed natural and powerful for geometry had, of course, no counterpart in the natural sciences. For example, no self-evident axioms could generate knowledge about a star's location, a plant's flowers, or an animal's teeth. Rather, one had to look at the world to see how things are. Accordingly, Aristotle devised an inductive–deductive method that used inductions from observations to infer general principles, deductions from those principles to check the principles against further observations, and additional cycles of induction and deduction to continue the advance of knowledge.

Aristotle gave natural science a tremendous boost. Ironically, his achievements are not often appreciated by contemporary scientists because he influenced certain raging debates about fundamentals that we now take for granted. It must be emphasized – even though modern readers can scarcely grasp how something so obvious to them could ever have been hotly debated – that Aristotle advanced science enormously and strategically simply by insisting that the physical world is real. Plato had diminished the reality or significance of the visible, physical world to an illusion – a derivative, fleeting shadow of the eternal, unreachable "Forms" that, Plato thought, composed true reality. But Aristotle rejected his teacher's theory of a dependent status for physical things, claiming rather an autonomous and real existence. "Moreover, the traits that give an individual object its character do not, Aristotle argued, have a prior and separate existence in a world of forms, but belong to the object itself. There is no perfect form of a dog, for example, existing independently in the world of forms and replicated imperfectly in individual dogs, imparting to them their attributes. For Aristotle, there were just individual dogs" (Lindberg 2007:46).

Another of Aristotle's immense contributions to science was to improve deductive logic. Aristotle's syllogistic logic was the first branch of mathematics to be based on axioms, pre-dating Euclid's geometry.

The greatest general deficiency of Aristotle's science was confusion about the integration and relative influences of philosophical presuppositions, empirical evidence, and deductive and inductive logic. How do all of these components fit together in a scientific method that can provide humans with considerable truth about the physical world? Aristotle's choice of geometry as the standard of success for the natural sciences amounts to asking deduction to do a job that can be done only by a scientific method that combines presuppositions, observational evidence, deduction, and induction. Aristotle never reconciled and integrated the deductivism in his ideal science and the empiricism in his actual science. Furthermore, the comforting notion that logic and geometry had special, self-evidently true axioms was destined to evaporate two millennia later with the discovery of nonstandard logics and non-Euclidean geometries. Inevitably, the natural sciences could not be just like geometry. The study of physical things and the study of abstract ideas could not proceed by identical methods.

The greatest specific deficiency of Aristotle's science was profound disinterest in manipulating nature to carry out experiments. For Aristotle, genuine science concerned undisturbed nature rather than dissected plants or manipulated rocks. Regrettably, his predilection to leave nature undisturbed greatly impeded the development of experimental science. Even in Aristotle's time, much about rudimentary experimental methods could have been learned from the simple trial-and-error procedures that had already been successful for improving agriculture and medicine. But for Aristotle, reflection on the practical arts was beneath the dignity of philosophers, so philosophy gained nothing from that prior experience with experimentation in other realms.

It is difficult to give a specific and meaningful number, but I would say that Aristotle got 70% of scientific method right. His contribution is impressive, especially for a philosopher-scientist living more than two millennia ago.

Augustine

Skipping forward seven centuries in this brief history of truth, from Aristotle to Augustine (AD 354–430), the standard of truth and grounds of truth had shifted considerably. Augustine is *the* towering intellect of Western civilization, the one and only individual whose influence dominated an entire millennium. He is remembered primarily as a theologian and philosopher – as a church father and saint. Yet his contribution to science was also substantial. Augustine's treatise on logic, *Principia dialecticae*, adopted Aristotle's logic (rather than its main competitor, Stoic logic), thereby ensuring great influence for Aristotle in subsequent medieval logic.

Lindberg (2007:150) has nicely summarized the relationship between science and the church in antiquity: "If we compare the early church with a modern research university or the National Science Foundation, the church will prove to have failed abysmally as a supporter of science and natural philosophy. But such a comparison is obviously unfair. If, instead, we compare the support given to the study of nature by the early church with the support available from any other contemporary social institution, it will become apparent that the church was the major patron of scientific learning."

For Augustine, the foremost standard of rationality and truth was not Euclid's geometry. Rather, it was Christian theology, revealed by God in Holy Scripture. Theology had the benefit of revelation from God, the All-Knowing Knower. Accordingly, theology replaced geometry as queen of the sciences and the standard of truth. But Augustine's view of how humans acquire even ordinary scientific knowledge relied heavily on divine illumination, particularly as set forth in *The Teacher* (King 1995). He "claimed that whatever one held to be true even in knowledge attained naturally – that is to say, without the special intervention of God as in prophecy or in glorification – one knew as such because God's light, the light of Truth, shone upon the mind" (Marrone 1983:5).

With beautiful simplicity and great enthusiasm, Augustine saw that truth is inherently objective, public, communal, and sharable: "We possess in the truth . . . what we all may enjoy, equally and in common; in it are no defects or limitations. For truth receives all its lovers without arousing their envy. It is open to all, yet it is always chaste. . . . The food of truth can never be stolen. There is nothing that you can drink of it which I cannot drink too. . . . Whatever you may take from truth and wisdom, they still remain complete for me" (Benjamin and Hackstaff 1964:69).

Augustine is also notable for his book against skepticism, *Against the Academicians*. He argued that skepticism was incoherent and that we can possess several kinds of knowledge impervious to skeptical doubts. Augustine defended the general reliability of sense perception. He appealed to common sense by asking if an influential skeptic, Carneades, knew whether he was a man or a bug! Conventional views of science's method and success continue to be challenged by skepticism and relativism, so Augustine's analysis remains relevant.

Medieval scholars

Moving forward another eight centuries in this brief history of truth, from Augustine, around AD 400, to the beginnings of medieval universities in the 1200s, the standard and grounds of scientific truth faced the most perplexing, exciting, and productive shift in the entire history of the philosophy of science. Some leading figures were Robert Grosseteste (*c.* 1168–1253) and later William of Ockham (*c.* 1285–1347) at the university in Oxford; William of Auvergne (*c.* 1180–1249), Albertus Magnus or Albert the Great (*c.* 1200–1280), and Thomas Aquinas (*c.* 1225–1274) at the university in Paris; and Roger Bacon (*c.* 1214–1294) and John Duns Scotus (*c.* 1265–1308) at both universities. The rise of universities happened to coincide with the rediscovery and wide circulation of Aristotle's books and their Arabic commentaries.

The immensely original contribution of those medieval scholars was to ask a new question about science's truth, a question that may seem ordinary now, but it had not previously been asked or answered. Indeed, after Augustine, eight centuries would pass before the question would be asked clearly, and still another century would pass before it would be answered satisfactorily. It is a slight variant on the most elemental question, placing emphasis on the human and social aspects of science. It can be expressed thus: What human-sized and public method can provide scientists with truth about the physical world? "Scholastics of the thirteenth and fourteenth centuries wanted to know how to identify that true knowledge which any intelligent person could have merely by exercising his or her natural intellectual capabilities" (Marrone 1983:3). They skillfully crafted a reinforced scientific method incorporating five great new ideas.

(1) Experimental Methods. Despite Aristotle's disinterest in manipulated nature, experimental methods were finally being developed in science, greatly expanding the opportunities to collect the specific data that could be used to discriminate effectively between competing hypotheses. Grosseteste was "the principal figure" in bringing about "a more adequate method of scientific inquiry" by which "medieval scientists were able eventually to outstrip their ancient European and Muslim teachers" (Dales 1973:62). He initiated a productive shift in science's emphasis, away from presuppositions and ancient authorities, and toward empirical evidence, controlled experiments, and mathematical descriptions. He combined the logic from philosophy and the empiricism from practical arts into a new scientific method. "He stands out from his contemporaries . . . because he, before anyone else, was able to see that the major problems to be investigated, if science was to progress, were those of scientific method. . . . He seems first to have worked out a methodology applicable to the physical world, and then to have applied it in the particular sciences" (A. C. Crombie, in Callus 1955:99, 101).

Roger Bacon, the Admirable Doctor, was influenced by Grosseteste. He expressed the heart of the new experimental science in terms of three great prerogatives. The first prerogative of experimental science was that conclusions reached by induction should be submitted to further experimental testing; the second prerogative was that experimental facts had priority over any initial presuppositions or reasons and could augment the factual basis of science; the third prerogative was that scientific research could be extended to entirely new problems, many with practical value. The Admirable Doctor conducted numerous experiments in optics. He was eloquent about science's power to benefit humanity.

(2) **Powerful Logic.** An army of brilliant medieval logicians greatly extended the deductive and inductive logic needed by science. That stronger logic, combined with the richer data coming from new experiments with manipulated objects, as well as traditional observations of unaltered nature, brought data to bear on theory choices with new rigor and power.

(3) **Theory Choice.** Medieval philosopher-scientists enriched science's criteria for choosing a theory. The most obvious criterion is that a theory must fit the data. Ordinarily, a theory is in trouble if it predicts or explains one thing but something else is observed. But awareness was growing that theories also had to satisfy additional criteria, such as parsimony.

William of Ockham, the Venerable Inceptor, is probably the medieval philosopher who is best known to contemporary scientists through the familiar principle of parsimony, often called "Ockham's razor." From Aristotle to Grosseteste, philosopher-scientists had valued parsimony, but Ockham advanced the discussion considerably. In essence, Ockham's razor advises scientists to prefer the simplest theory among those that fit the data equally well. Ockham's rejection, on grounds of parsimony, of Aristotle's theory of impetus paved the way for Newton's theory of inertia.

(4) **Science's Presuppositions.** Albertus Magnus, the Universal Doctor, handled science's presuppositions with exquisite finesse, as will be elaborated in Chapter 5. He gave Aristotle the most painstaking attention yet, writing more

than 8,000 pages of commentary. Albertus Magnus grounded science in common sense. For instance, seeing someone sitting justifies the belief that such is the truth. That common-sense grounding enabled the Universal Doctor to grant science considerable intellectual independence from worldview presuppositions and theological disputes.

Thomas Aquinas, the Angelic Doctor, was an enormously influential student of Albertus Magnus, and he accepted his teacher's view of science. Aquinas's support alone would have been sufficient to ensure widespread acceptance in all medieval universities of Albertus's approach for legitimating presuppositions and demarcating science. Although primarily a theologian, the Angelic Doctor also wrote extensive commentaries on several of Aristotle's books, including the *Physics*.

(5) Scientific Truth. Finally, medieval philosopher-scientists adopted a conception of scientific truth that was more broad, fitting, and attainable than had Aristotle. Ockham "made a distinction between the science of real entities (*scientia realis*), which was concerned with what was known by experience to exist and in which names stood for things existing in nature, and the science of logical entities (*scientia rationalis*), which was concerned with logical constructions and in which names stood merely for concepts" (Crombie 1962:172). Thus, the natural sciences had quit trying to be just like geometry.

Those five great ideas account for much of the medieval reinforcement of scientific method that vitalized science's pursuit of truth. The main deficiencies of Aristotelian science were remedied in the thirteenth century. Experiments with manipulated objects were seen to provide relevant data with which to test hypotheses. Also, a workable integration of presuppositions, evidence, and logic emerged that endowed scientific method with accessible truth. Medieval philosopher-scientists also demarcated science apart from philosophy and theology, thereby granting science substantial intellectual and even institutional independence.

The thirteenth century began with a scientific method that lacked experimental methods and lacked an approach to truth that applied naturally to physical things. It concluded with an essentially complete scientific method with a workable notion of truth. Because of Robert Grosseteste at Oxford, Albertus Magnus at Paris, and other medieval scholars, it was the golden age of scientific method. No other century has seen such a great advance in scientific method. The long struggle of sixteen centuries, from Aristotle to Aquinas, had succeeded at last in producing an articulated and workable scientific method with a viable conception of truth. Science had come of age. From the prestigious universities in Oxford and Paris, the new experimental science of Robert Grosseteste and Roger Bacon spread rapidly throughout the medieval universities: "And so it went to Galileo, William Gilbert, Francis Bacon, William Harvey, Descartes, Robert Hooke, Newton, Leibniz, and the world of the seventeenth century" (Crombie 1962:15). So it went to us also.

Modern scholars

Skipping forward a final time in this brief history of truth, science's method and concept of truth have been developed further in modern times beginning around 1500. Developments after 1960, which have been the primary determinants of the current scene, will be taken up in greater detail in the next chapter.

The development of increasingly powerful scientific instruments has been a prominent feature of scientific method during the modern era. An influential early example was the observatory of Tycho Brahe (1546–1601), with an unprecedented accuracy of four minutes of arc, nearly the limit possible without a telescope. Galileo Galilei (1564–1642) constructed an early telescope and invented the first thermometer. He carefully estimated measurement errors and took them into account when fitting models to his data. Blaise Pascal (1623–1662) invented the barometer and an early calculating machine.

Mathematical tools were also advanced. Pascal, Pierre de Fermat (1601–1665), Jacob Bernoulli (1654–1705), Thomas Bayes (1701–1761), and others developed probability theory and elementary statistics. Sir Isaac Newton (1642–1727) and Gottfried Leibniz (1646–1716) invented calculus. Thomas Reid (1710–1796) invented a non-Euclidean geometry in 1764. That discovery, that Euclid's axioms are not uniquely self-evident and true, further eroded the ancient reputation of geometry as the paradigmatic science. Although syllogistic logic was axiomatized by Aristotle, and geometry by Euclid, about 23 centuries ago, arithmetic was first axiomatized by Giuseppe Peano (1858–1932) a mere one century ago.

Sir Francis Bacon (1561–1626) popularized the application of science to the furtherance of mankind's estate with his enduring slogan, "Knowledge is power." His attempt to win financial support for science from the English crown failed in his own lifetime but bore fruit shortly thereafter.

In 1562, the French scholar Henri Etienne (1531–1598) first printed, in Latin translation, the *Outlines of Pyrrhonism*, by the ancient skeptic Sextus Empiricus (*fl.* AD 150). "It was the rediscovery of Sextus and of Greek scepticism which shaped the course of philosophy for the next three hundred years" (Annas and Barnes 1985:5). That the preceding millennium had struggled rather little with skepticism may have been due to the perception that Augustine's refutation sufficed. But René Descartes (1596–1650), George Berkeley (1685–1753), David Hume (1711–1776), Immanuel Kant (1724–1804), and other modern thinkers struggled mightily with Sextus' challenges.

"In his *Outlines of Pyrrhonism* Sextus defends the conclusions of Pyrrhonian scepticism, that our faculties are such that we ought to suspend judgement on all matters of reality and content ourselves with appearances" (Woolhouse 1988:4). The skeptics' opponents, to use their own term, were the "dogmatists" who believed that truth was attainable. Sextus observed that two criteria for discovering truth were offered: reason by the rationalists, and the senses by the empiricists. He argued that neither reason nor sense perception could guarantee truth. To a considerable extent, the philosophies of Descartes and Leibniz can be understood as attempts to make reason work despite Sextus' skeptical criticisms. Likewise, the philosophies of Francis Bacon and Locke attempt to make sense perception and empirical data work despite the ordeal by skepticism. So, although quite different, rationalism and empiricism had in common the same opponent, skepticism. Chatalian (1991) argued persuasively that the Greek skeptics, Pyrrho of Elis (*c.* 360–270 BC) and Sextus Empiricus, were often superficially studied and poorly understood. Nevertheless, rationalism and empiricism sought to guard truth from skepticism's attacks.

René Descartes exemplified rationalism, which emphasized philosophical reasoning as the surest source of truth rather than uncertain observations and risky inductions. Descartes agreed with Francis Bacon that science had both general principles and individual observations, but his progression was the reverse. The empiricist Bacon sought to collect empirical data and then progress inductively to general relations, whereas the rationalist Descartes sought to begin with general philosophical principles and then deduce the details of expected data. To obtain the needed stockpile of indubitable general principles, Descartes's method was to reject the unverified assumptions of ancient authorities and begin with universal doubt, starting afresh with that which is most certain.

His chosen starting point for indubitable truth was his famous "*Cogito ergo sum*," "I think, therefore I exist." He then moved on to establish the existence of God, whose goodness assured humans that their sense perceptions were not utterly deceptive, so they could conclude that the physical world exists.

George Berkeley was an empiricist. The battle cry of empiricists was back to experience. In essence, "an empiricist will seek to relate the contents of our minds, our knowledge and beliefs, and their acquisition, to sense-based experience and observation. He will hold that experience is the touchstone of truth and meaning, and that we cannot know, or even sensibly speak of, things which go beyond our experience" (Woolhouse 1988:2). Berkeley was also an idealist, believing that only minds and ideas exist, not the physical world.

Berkeley applauded Newton's careful distinction between mathematical axioms and empirical applications, in essence, between ideas and things. But Berkeley was concerned that such a distinction would invite a dreaded skepticism: "Once a distinction is made between our perceptions of material things and those things themselves, 'then are we involved all in *scepticism*'. For it follows from this distinction that we see only the appearances of things, images of them in our minds, not the things themselves, 'so that, for aught we know, all we see, hear, and feel, may be only phantom and vain chimera, and not at all agree with the real things'" (Woolhouse 1988:110). What was the solution? "Faced with the evidently troublesome distinction between things and ideas, Berkeley in effect collapses it; he concludes that *ideas are things.* As he explains, 'Those immediate objects of perception, which according to [some] . . . are only appearances of things, I take to be the real things themselves'" (Woolhouse 1988:113). Ideas and minds were all of reality; there were no such things as physical objects. Accordingly, science's proper goal was to account for the mind's experiences and perceptions, rather than an external physical reality.

Isaac Newton continued Aquinas's broad perspective on truth in science, in contrast to Aristotle's narrow vision. Newton believed that science could make valid assertions about unobservable entities and properties. For example, from the hardness of observable objects, one could infer the hardness of their constituent particles that were too small to be observed. He also believed that science should generally trust induction: "In experimental philosophy we are to look upon propositions inferred by general induction from phenomena as accurately or very nearly true, notwithstanding any contrary hypotheses that may be imagined, till such time as other phenomena occur, by which they may either be made more accurate, or liable to exceptions" (Cajori 1947:400). Also, Newton insisted, contrary to Leibniz, that science could claim legitimate knowledge even in the absence of deep explanation. Thus, the observed inverse-square law applying to gravitational attraction counted as real knowledge, even without any deep understanding of the nature or cause of gravity.

Newton's view of scientific method, which has influenced modern science so strongly, corresponded with that of Grosseteste: "Of his 'Rules of Reasoning in Philosophy' the first, second, and fourth were, respectively, the well-established principles of economy [parsimony], uniformity, and experimental verification and falsification, and the third was a derivative of these three. And when he came to describe his method in full, he described precisely the double procedure that had been worked out since Grosseteste in the thirteenth century," namely, induction of generalities from numerous observations, and deduction of specific predictions from generalities (Crombie 1962:317). "We reach the conclusion that despite the enormous increase in power that the new mathematics brought in the seventeenth century, the logical structure and problems of experimental science had remained basically the same since the beginning of its modern history some four centuries earlier" (Crombie 1962:318).

David Hume could be considered an empiricist or a skeptic. "Among all the philosophers who wrote before the twentieth century none is more important for the philosophy of science than David Hume. This is because Hume is widely recognized to have been the chief philosophical inspiration of the most important twentieth-century school in the philosophy of science – the so-called logical positivists," also called logical empiricists (Alexander Rosenberg, in Norton 1993:64). Hume admired Francis Bacon and greatly admired Newton, "the greatest and rarest genius that ever rose for the ornament and instruction of the species" (Woolhouse 1988:135). Hume took himself to be discovering a science of man, or principles of human understanding more specifically, that was akin to Newton's science of mechanics in its method and rigor.

Hume's analysis began with two fundamental moves. First, he insisted that the objective was *human* understanding, so he examined human nature to assess our mental capacities and limitations. "There is no question of importance, whose decision is not compriz'd in the science of man; and there is none, which can be decided with any certainty, before we become acquainted with that science" (John Biro, in Norton 1993:34). Second, Hume rigorously adopted an empiricist theory of meaning, requiring statements to be grounded in experience, that is, in sense perceptions and ideas based on them. "As to those *impressions*, which arise from the *senses*, their ultimate cause is, in my opinion, perfectly inexplicable by human reason, and 'twill always be impossible to decide with certainty, whether they arise immediately from the object, or are produc'd by the creative power of the mind, or are deriv'd from the author of our being. Nor is such a question any way material to our present purpose. We may draw inferences from the coherence of our perceptions, whether they be true or false; whether they represent nature justly, or be mere illusions of the senses" (David F. Norton, in Norton 1993:6–7).

It is difficult to induce contemporary scientists, who think that rocks and trees are real and knowable, to grasp the earnestness of Hume's empiricism. Hume's empiricist science concerned mental perceptions, not physical things. His concern was with "our perceptions, qua perceptions, with perceptions as, simply, the *elements or objects of the mind* and not as *representations* of external existences" (David F. Norton, in Norton 1993:8). For example, he was concerned with our mental perceptions and ideas of trees, not with trees as external physical objects. Accordingly, to report that "I see a tree" was, for Hume, a philosophical blunder, because this "I see" posits a mental perception, while this "tree" posits a corresponding physical object. He called that blunder the "double existence" (or "representational realism") theory – "the theory that while we experience only impressions and ideas, there is also another set of existences, namely objects" (Alexander Rosenberg, in Norton 1993:69). Of course, earlier thinkers, like Aristotle, had a more flattering name for that theory, the correspondence theory of truth. Anyway, for Hume, the corrected report would read something like "I am being appeared to treely," which skillfully avoids the double existence of perceptions and objects and instead confines itself to the single existence of perceptions.

So although Hume's avowed hero was Newton, their philosophies of science were strikingly different because Newton's science concerned truth about a knowable physical world. Hume and Newton could agree on the truism that science was done by scientists – by humans. But Hume's "humans" were post-skeptical philosophers, whereas Newton's "humans" were common-sensical scientists. Likewise, Hume's "observations" were strictly mental perceptions, whereas Newton's "observations" were sensory responses corresponding reliably to external physical objects. Hume says, "I am being appeared to treely," but Newton says "I see a tree."

Thomas Reid, quite in contrast to his fellow Scot David Hume, grounded philosophy in an initial appeal to common sense, as in this quotation from Hamilton's edition of Reid's work:

> Philosophy . . . has no other root but the principles of Common Sense; it grows out of them, and draws its nourishment from them. Severed from this root, its honours wither, its sap is dried up, it dies and rots. . . . It is a bold philosophy that rejects, without ceremony, principles which irresistibly govern the belief and the conduct of all mankind in the common concerns of life: and to which the philosopher himself must yield, after he imagines he hath confuted them. Such principles [of common sense] are older, and of more authority, than Philosophy: she rests upon them as her basis, not they upon her. (Hamilton 1872:101–102)

Wolterstorff offers an insightful commentary on this passage from Reid:

> The philosopher has no option but to join with the rest of humanity in conducting his thinking within the confines of common sense. He cannot lift himself above the herd. . . .
>
> Alternatively, philosophers sometimes insist that it is the calling of the philosopher to *justify* the principles of common sense – not to reject them but to ground them. Close scrutiny shows that this too is a vain attempt; all justification takes for granted one or more of the principles. Philosophical thought, like all thought and practice, rests at bottom not on grounding but on trust. (Nicholas Wolterstorff, in Cuneo and van Woudenberg 2004:77–78)

Reid avoided the hopeless attempt to make natural science just like geometry by accepting both the deductions of geometry and the reliability of observation:

> That there is such a city as Rome, I am as certain as of any proposition in Euclid; but the evidence is not demonstrative, but of that kind which philosophers call probable. Yet, in common language, it would sound oddly to say, it is probable there is such a city as Rome, because it would imply some degree of doubt or uncertainty. (Hamilton 1872:482)

Representing common sense as eyes and philosophy as a telescope, Reid offered the analogy that a telescope can help a man see farther if he has eyes, but will show nothing to a man without eyes (Hamilton 1872:130). Accordingly, to the partial skeptic, Reid commended a dose of common sense as the best remedy; but to the total skeptic, Reid had nothing to say. Reid could give a man a telescope but not eyes.

Exactly what does Reid mean by common sense? He listed 12 principles as a sampling from the totality of such principles (Nicholas Wolterstorff, in Cuneo and van Woudenberg 2004:78–79). For example, these principles include "that the thoughts of which I am conscious are the thoughts of a being which I call myself" and "that there is life and intelligence in our fellow men with whom we converse" and "that those things do really exist which we distinctly perceive by our senses." The general reliability of sense perception looms large in Reid's writings (James van Cleve, in Cuneo and van Woudenberg 2004:101–133).

Immanuel Kant devised a new variant of rationalism intended to divert Hume's skepticism and to support a thoroughly subjective, human-sized version of scientific truth. His influential *Critique of Pure Reason* (1781, revised 1787) was followed by a popularization, the *Prolegomena to any Future Metaphysics That Shall Come Forth as Scientific* (1783). He was not happy with his predecessors. Against Descartes, Hume, Berkeley, and Reid and their failed metaphysics, Kant promised us a keen pilot that can steer our metaphysical ship safely. But Kant's thinking is remarkably complex and subtle.

Fortunately, however, the opening pages of his *Prolegomena* lead us quickly into the very heart of enduring themes in his philosophy of science. The centerpiece is his response to Hume's problem of causality. In the entire history of metaphysics, "nothing has ever happened which was more decisive to its fate than the attack made upon it by David Hume," specifically the attack upon "a single but important concept in Metaphysics, viz., that of Cause and Effect" (Carus 1902:3–4).

The problem with causality, or any other general law of nature, was that such laws made claims that went beyond any possible empirical support. Empirical evidence for a causal law could only be of the form "All instances of *A* observed in the past were followed by *B*," whereas the law asserted the far grander claim that "All instances of *A*, observed or not and past or future, are followed by *B*." But that extension was inductive, excessive, and uncertain, exceeding its evidence. Consequently, something else had to be added to secure such a law.

Accordingly, Kant's solution combined two resources: a general philosophical principle of causality asserted by *a priori* reasoning, and specific causal laws discovered by *a posteriori* empirical observation and induction. By that combination, "particular empirical laws or uniformities are subsumed under the *a priori* concept of causality in such a way that they thereby become necessary and acquire a more than merely inductive status" (Michael Friedman, in Guyer 1992:173). For example, "The rule of uniformity according to which illuminated bodies happen to become warm is at first merely empirical and inductive; if it is to count as a genuine law of nature, however, this same empirical uniformity must be subsumed under the *a priori* concept of causality, whereupon it then becomes necessary and strictly universal" (Michael Friedman, in Guyer 1992:173). Thus, a general principle of causality upgraded the evidence for particular causal laws.

Moving forward about a century after Kant to almost a century ago, the period around 1920 was pivotal for the philosophy and method of science. Although the current scene is one of vigorous debate among several sizable schools, for a few decades following 1920, a single school dominated, logical empiricism (also called logical positivism, just positivism, and the Vienna Circle). Some of the leading members, associates, visitors, and collaborators were A. J. Ayer, Rudolf

Carnap, Albert Einstein, Herbert Feigl, Philip Frank, Kurt Gödel, Hans Hahn, C. G. Hempel, Ernest Nagel, Otto Neurath, W. V. Quine, Hans Reichenbach, Moritz Schlick, and Richard von Mises. Sir Karl Popper, who would become the circle's most influential critic, often attended but was not a member or associate. "Almost all work, foundational or applied, in English-language philosophy of science during the present century has either been produced within the tradition of logical empiricism or has been written in response to it. Indeed it is arguable that philosophy of science as an academic discipline is essentially a creation of logical empiricists and (derivatively) of the philosophical controversies that they sparked" (Richard Boyd, in Boyd, Gasper, and Trout 1991:3).

As its apt name suggests, "logical empiricism" combines logic and empiricism. "Logical empiricism arose in the twentieth century as a result of efforts by scientifically inclined philosophers to articulate the insights of traditional empiricism, especially the views of Hume, using newer developments in mathematical logic" (Richard Boyd, in Boyd et al. 1991:5). The central idea was to limit meaningful scientific statements to sensory-experience reports and logical inferences based on those reports. Considered separately, the rationalist tradition with its logic and the empiricist tradition with its sensory experience were deemed inadequate for science, but a clever integration of logic and experience was expected to work.

However, presuppositions were not part of logical empiricism. Indeed, "the fundamental motivation for logical empiricism" was "the elimination of metaphysics," including "doctrines about the fundamental nature of substances," "theological matters," and "our relation to external objects" (Richard Boyd, in Boyd et al. 1991:6). The perceived problem with metaphysical presuppositions was that they were not truths demonstrable by logic, and neither were they demonstrable by observational data, so for a logical empiricist, such ideas were just nonsense. Accordingly, science and philosophy parted ways. "The Circle rejected the need for a specifically philosophical epistemology that bestowed justification on knowledge claims from beyond science itself" (Thomas Uebel, in Audi 1999:956).

Clearly, the motivation of logical empiricism was to create a purified, hard, no-nonsense version of science based on solid data and avoiding philosophical speculation. Yet serious problems emerged that eroded its credibility by 1960.

Regrettably, logical empiricism rejected two medieval insights that have since been restored to their vital roles in philosophy of science. First, the innovation of the logical empiricists was not their combining of logic and empirical evidence, for their medieval predecessors had already done that several centuries earlier, but rather was in their rejection of presuppositions, especially metaphysical presuppositions about what exists. By dismissing presuppositions, science parted ways not only with philosophy but also with common sense. Even the primitive theory, for instance, that a person's perception of a cat results from the eyes seeing an actual physical cat *is* a metaphysical theory about what exists. "Given such a view" as logical empiricism, "difficult epistemological gaps arise between available evidence and the commonsense conclusions we want to reach about the world around us," including "enormous difficulty explaining how what we know about sensations could confirm for us assertions about an objective physical world" (Richard A. Fumerton, in Audi 1999:515).

Second, medieval scholars had engaged the practical question: What human-sized and public method can provide scientists with truth about the physical world? But logical empiricism's stringent science used logic and data in a rather mechanical fashion, guaranteed to be scientific and to guard truth, while largely disregarding human factors. The rapid dismantling of logical empiricism around 1960 was a reaction against this science lacking a human face.

Water

An objective announced at the beginning of the previous chapter is to enable readers to comprehend a statement such as "Water is H_2O" in its full philosophical and scientific richness. That chapter explained the meanings of science's four bold claims: rationality, truth, objectivity, and realism. This chapter has presented the intellectual history of the concept of truth as applied to the physical world. With this philosophical and historical background in place, the additional scientific information can now be added to complete the story about water.

What things are made of was one of the principal scientific questions that began to be asked in antiquity:

> Thales of Miletos, who lived in about 600 BC, was the first we know of who tried to explain the world not in terms of myths but in more concrete terms, terms that might be subject to verification. What, he wondered might the world be made of? His unexpected answer was: water. Water could clearly change its form from solid to liquid to gas and back again; clouds and rivers were in essence watery; and water was essential for life. His suggestion was fantastical perhaps, but such unnatural thoughts – contrary to common sense – are often the essence of science. But more important than his answer was his explicit attempt to find a fundamental unity in nature. (Wolpert 1993:35)

Thales of Miletos (*c.* 625–546 BC) got the wrong answer about water, but Wolpert credited him for being in essence the first scientist because he was asking the right question. And that was quite an innovation indeed! But about two and a half millennia later, the right answer about water's composition has finally emerged.

In 1800, William Nicholson decomposed water into H_2 and O_2 by electrolysis, but it remained until 1805 for Joseph Louis Gay-Lussac and Alexander von Humboldt to discover the proper ratio of two parts H_2 and one part O_2, and hence the chemical formula H_2O. Furthermore, these two gases can be ignited and thereby recombined to reconstitute the water. These simple experiments are easily replicated in high school or college chemistry classes (Eggen et al. 2012).

That table salt is NaCl was discovered a few years later. The element sodium was discovered in 1807 by Sir Humphry Davy by electrolysis of molten sodium hydroxide and the element chlorine in 1810 by Davy (by repeating an earlier experiment of 1774 by Karl Wilhelm Scheele whose reaction of MnO_2 and HCl produced chlorine gas but without Scheele understanding that chlorine is an element). Hence, table salt is a compound of a caustic metal and a poisonous gas.

The nature of a chemical element, such as hydrogen or chlorine, was illuminated substantially by the invention of the periodic table of the chemical elements by Dmitri Mendeleev in 1869. Ernest Rutherford discovered the atomic nucleus in 1911, and that same year Robert Millikan and Harvey Fletcher published an accurate measurement of an electron's charge. Within a decade, chemists understood that the place of each element in the periodic table is determined by the number of protons in its nucleus. In another decade, they discovered neutrons, which are also in atomic nuclei and have a mass nearly the same as protons. At long last, there was a rather satisfactory understanding of a chemical element. Hydrogen and oxygen are elements 1 and 8, and sodium and chlorine are elements 11 and 17 in the periodic table.

Chemists further discovered that a given element can have several isotopes due to its atoms having the same number of protons but different numbers of neutrons. For instance, hydrogen has three naturally occurring isotopes with zero to two neutrons denoted by ^1H to ^3H, and oxygen has three naturally occurring isotopes with eight to ten neutrons denoted by ^{16}O to ^{18}O. Accordingly, pure water has 18 distinguishable kinds of H_2O molecules – and about 2 per billion of these molecules are dissociated into H^+ ions of 3 kinds and OH^- ions of 9 kinds, for a total of 30 constituents (although more than 99% of water is a single constituent, H_2O molecules composed of the most common isotopes, ^1H and ^{16}O). Even deeper understanding of matter continues with the discovery that protons and neutrons are composed of quarks and gluons, but that goes beyond what needs to be discussed here.

To recapitulate the story of water, it began with Thales asking what things are made of. It progressed with Aristotle who, unlike Plato, insisted that physical objects are thoroughly real. It advanced with medieval philosopher-scientists finally asking and answering the most elemental question about scientific method: What inputs are required for us humans to reach true conclusions about the physical world? It further advanced with the scientific revolution in the 1600s and 1700s. Finally, scientific discoveries from about 1800 to 1930 clarified the atomic makeup of the elements hydrogen and oxygen that combine to form water. To properly comprehend that "Water is H_2O," one must understand not only the relevant scientific discoveries since 1800 but also the indispensable philosophical and historical background beginning around 600 BC that gives meaning and credence to a scientific claim of rationality, truth, objectivity, and realism.

Summary

To understand science's method and claims in historical perspective, this brief history of truth has examined the standards and evidence expected for truth claims during the past 23 centuries, from Aristotle to 1960. The most elemental question remains: What inputs must go in so that scientific conclusions can come out? Aristotle got much of scientific method right, but he disregarded experimental methods and had a somewhat confused expectation that a mature version of the natural sciences should be much like geometry in its method and certainty. Those deficiencies were remedied in the fledgling medieval universities in the 1200s. From 1500 to the present, tremendous advances have been made, especially regarding deductive and inductive logic, instruments for collecting data, and computers for analyzing data.

History reveals a tremendous diversity of views on science. Rationalists emphasized reason and logic; empiricists emphasized sensory experience and empirical evidence; and logical empiricists combined logic and empirical evidence while attempting to avoid presuppositions. Science's presupposition of a real and comprehensible world has had two versions: the worried version of skeptics such as Pyrrho of Elis and Sextus Empiricus, and the confident version of Albertus Magnus, Isaac Newton, and Thomas Reid. At this time in history, the way ahead for science's general methodological principles will require a deep integration of these three inputs: presuppositions, evidence, and logic. This is necessary to support science's four bold claims: rationality, truth, objectivity, and realism.

Study questions

(1) The most elemental question about scientific method concerns the inputs required for us humans to reach true conclusions about the physical world. What are the three inputs identified in this chapter, and which of these inputs were emphasized by rationalists, empiricists, and skeptics?
(2) What aspects of scientific method do you think Aristotle got right, and what other important aspects remained to be clarified by later philosopher-scientists?
(3) What were Augustine's contributions to science?
(4) What were the five great ideas of medieval philosopher-scientists that advanced science greatly?

(5) Recall the diverse views on science of Descartes, Berkeley, Newton, Hume, Reid, and Kant, and then select one who you find particularly interesting. Which of his ideas most intrigue you, and do you think that those particular ideas have stood the test of time as indicated by their still being accepted as important ideas in contemporary science?