Introduction

Science and technology have immense cultural and economic significance. They transform much of what we encounter in daily life. Obvious examples are the computers, phones, and consumer electronics that change and improve noticeably on a timescale of merely a year. For instance, compared to the first flash drive for my computer that I purchased in the early 2000s, now a faster and smaller flash drive with 64 times as much memory costs only a quarter as much. This equates to the memory per dollar almost doubling annually.

Furthermore, scientific transformation is pervasive, even when not so obvious. For instance, a simple loaf of bread or bowl of rice seems like a low-tech product that is the same as it was decades ago. Not so! Wheat rust, rice blast, and other crop diseases are continually evolving new virulent strains that threaten current crop varieties. The ongoing efforts of plant breeders are necessary to protect crops from diseases, to increase yields, and to improve nutritional and other traits. The rate of change for our crops is so rapid that few varieties are still competitive after only seven or eight years. Were plant breeders to stop their work, the disease problems within a decade for wheat, rice, corn, potatoes, and other major crops would be catastrophic. So, the loaf of bread that you buy today, or the bowl of rice that you eat today, is a high-tech product that sophisticated and energetic scientific efforts have rendered quite different from its predecessors of a decade ago. My own scientific work from 1970 to the present has been developing statistical methods and software for these agricultural researchers.

Besides its obvious economic impact, science has an equally significant cultural importance. The knowledge that science has gained affects how we understand ourselves and our world. Discoveries by Galileo, Newton, Faraday, and Darwin changed science but also impacted culture. The substantial interaction between science and culture raises momentous questions about how best to integrate the sciences and the humanities in an overall approach to knowledge and life.

This book has one thesis, two purposes, and an intended audience. The thesis of this book is that scientific methodology has two components, the general principles of scientific method and the research techniques of a given specialty, and the winning combination for scientists is strength in both. This book's two purposes, set forth in its preface, are to increase productivity by understanding scientific method more deeply and to gain perspective from a distinctively humanities-rich vision of science. The intended audience is persons undertaking their first systematic study of scientific method, spanning undergraduates to professionals in both the sciences and the humanities.

The gateway into science

Given the great intrinsic, cultural, and economic significance of science, its most essential feature has tremendous importance: its gateway. Scientific method, which is the topic of this book, is the gateway into science and technology. This gateway was discovered merely a few centuries ago, between 1200 and 1600 by various accounts, long after civilizations had risen and fallen around the globe for millennia. People are not born knowing about scientific method, and many of its features are counter-intuitive and hence difficult to grasp. Consequently, scientific method requires systematic study. As the gateway into science, scientific method precedes scientific discovery, which precedes technological advances and cultural influences.

The structure of science's methodology envisioned here is depicted in Figure 1.1, which shows individual sciences, such as astronomy and chemistry, as being partly similar and partly dissimilar in methodology. What they share is a core of the general principles of scientific method. This common core includes such topics as hypothesis generation and testing, deductive and inductive logic, parsimony, and science's presuppositions, domain, and limits. Beyond methodology as such, some practical issues are shared broadly across the sciences, such as relating the scientific enterprise to the humanities, implementing effective science education, and clarifying science's ethics.

The general principles that constitute this book's topics are shown in greater detail in Figure 1.2. These principles can be described in three groups, moving from the outermost to the innermost parts of this figure.

(1) Some principles are relatively distinctive of science itself. For instance, the ideas about parsimony and Ockham's hill that are developed in Chapter 10 have a distinctively scientific character.

(2) Other principles are shared broadly among all forms of rational inquiry. For example, deductive logic is squarely in the province of scientists, as explored in Chapter 7, but deductions are also important in nearly all undertakings.

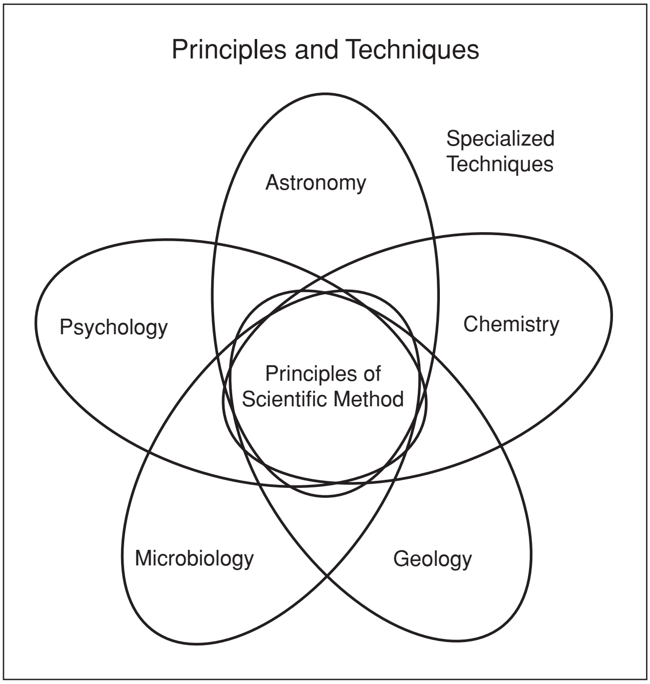

Figure 1.1 Science's methodology depicted for five representative scientific disciplines, which are partly similar and partly dissimilar. Accordingly, scientific methodology has two components. The general principles of scientific method pervade the entire scientific enterprise, whereas specialized techniques are confined to particular disciplines or subdisciplines.

(3) Still other principles are so rudimentary and foundational that their wellsprings are in common sense. This includes science's presuppositions of a real and comprehensible world, which are discussed in Chapter 5.

Naturally, the boundaries among these three groups are somewhat fuzzy, so they are shown with dashed lines. Nevertheless, the broad distinctions among these three groups are clear and useful.

There is a salient difference between specialized techniques and general principles in terms of how they are taught and learned. Precisely because specialized techniques are specialized, each scientific specialty has its own more or less distinctive set of techniques. Given hundreds of specialties and subspecialties, the overall job of communicating these techniques requires countless courses, books, and articles. But precisely because general principles are general, the entire scientific community has a single shared set of principles, and it is feasible to collect and communicate the main information about these principles within the scope of a single course or book. Whereas a scientist or technologist

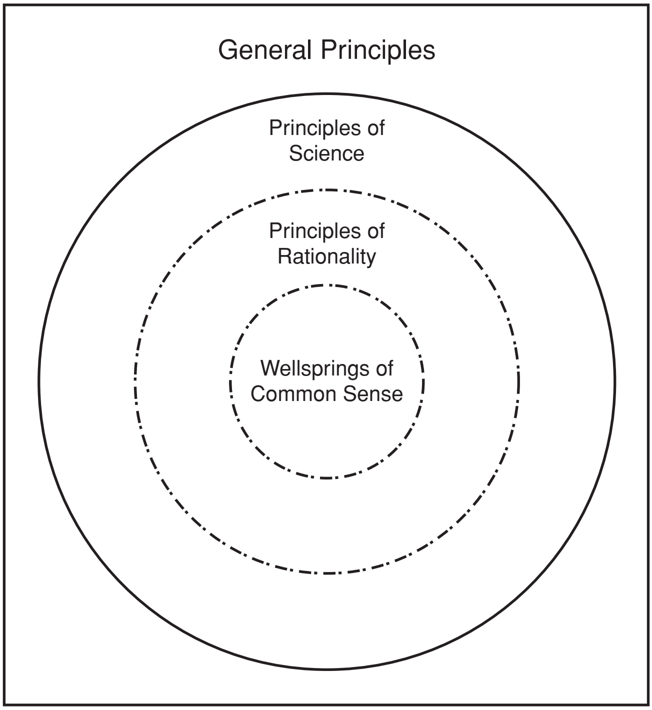

Figure 1.2 **Detailed view of the general principles, which are of three kinds: principles that are relatively distinctive of science itself, broader principles found in all forms of rational inquiry, and foundational principles with their wellsprings in common sense.**

needs to learn new techniques when moving from one project to another, the pervasive general principles need be mastered but once. Likewise, whereas specialized techniques and knowledge have increasingly shorter half-lives, given the unprecedented and accelerating rate of change in science and technology, the general principles are refreshingly enduring.

What a scientist or technologist needs in order to function effectively can be depicted by a resources inventory, as in Figure 1.3. All items in this inventory are needed for successful research. The first three items address the obvious physical setup that a scientist needs. The last two items are intellectual rather than physical, namely, mastery of the specialized techniques of a chosen specialty and mastery of the general principles of scientific method.

Frequently, the weakest link in a scientist's inventory is an inadequate understanding of science's principles. This weakness has just as much potential to retard progress as does, say, inappropriate laboratory equipment or inadequate training in some research technique.

Scientific Resources Inventory

☑ Laboratory equipment to generate data
☑ Computers and software to analyze data
☑ Infrastructure: colleagues, libraries, Internet access
☑ Technical training in research specialty
☐ General principles of scientific method

Figure 1.3 A typical resources inventory for a research group. The scientists in a given research group often have excellent laboratory equipment, computers, infrastructure, and technical training, but inadequate understanding of the general principles of scientific method is the weakest link. Ideally, a research group will be able to check off all five boxes in this inventory, and there will be no weak link.

A controversial idea

The mere idea that there exist such things as general principles of scientific method is controversial. The objections are of two kinds: philosophical and scientific. But first, a potential misunderstanding needs to be avoided. The scientific method "is often misrepresented as a fixed sequence of steps," rather than being seen for what it truly is, "a highly variable and creative process" (AAAS 2000:18). The claim of this book is that science has general principles that must be mastered to increase productivity and enhance perspective, not that these principles provide a simple and automated sequence of steps to follow.

Beginning with the philosophical objection, it is fashionable among some skeptical, relativistic, and postmodern philosophers to say that there are no principles of rationality whatsoever that reliably or impressively find truth. For instance, in an interview in *Scientific American*, the noted philosopher of science, Paul Feyerabend, insisted that there are no objective standards of rationality, so consequently there is no logic or method to science (Horgan 1993). Instead, "Anything goes" in science, and it is no more productive of truth than "ancient myth-tellers, troubadours and court jesters." From that dark and despairing philosophical perspective, the concern with scientific method would seem to have nothing to do distinctively with science itself. Rather, science would be just one more instance of the pervasive problem that rationality and truth elude us mere mortals, forever and inevitably.

Such critiques are unfamiliar to most scientists, although some may have heard a few distant shots from the so-called science wars. Scientists typically find those objections either silly or aggravating, so rather few engage such controversies. But in the humanities, those deep critiques of rationality are currently influential. By that reckoning, Figure 1.1 should show blank paper, with neither general principles nor specialized techniques that succeed in finding truth.

Moving along to the scientific objection, some scientists have claimed that there is no such thing as a scientific method. For instance, a Nobel laureate in medicine, Sir Peter Medawar, pondered this question: "What methods of enquiry apply with equal efficacy to atoms and stars and genes? What *is* 'The Scientific Method'?" He concluded that "I very much doubt whether a methodology based on the intellectual practices of physicists and biologists (supposing that methodology to be sound) would be of any great use to sociologists" (Medawar 1969:8, 13). By that reckoning, Figure 1.1 should show the methodologies of the individual sciences dispersed, with no area in which they would all overlap.

Is it plausible that, contrary to Figure 1.1, the methodologies of the various branches of science have no overlap, no shared general principles? Asking a few concrete questions should clarify the issues. Do astronomers use deductive logic, but not microbiologists? Do psychologists use inductive logic (including statistics) to draw conclusions from data, but not geologists? Are probability concepts and calculations used in biology, but not in sociology? Do medical researchers care about parsimonious models and explanations, but not electrical engineers? Does physics have presuppositions about the existence and comprehensibility of the physical world, but not genetics? If the answers to such questions are no, then Figure 1.1 stands as a plausible picture of science's methodology.

The AAAS position on method

Beyond such brief and rudimentary reasoning about science's methodology, it merits mention that the thesis proposed here accords with the official position of the American Association for the Advancement of Science (AAAS). The AAAS is the world's largest scientific society, the umbrella organization for almost 300 scientific organizations and publisher of the prestigious journal *Science*. Accordingly, the AAAS position bids fair as an expression of mainstream science. The AAAS views scientific methodology as a combination of general principles and specialized techniques, as depicted in Figure 1.1.

> Scientists share certain basic beliefs and attitudes about what they do and how they view their work.... Fundamentally, the various scientific disciplines are alike in their reliance on evidence, the use of hypotheses and theories, the kinds of logic used, and much more. Nevertheless, scientists differ greatly from one another in what phenomena they investigate and in how they go about their work; in the reliance they place on historical data or on experimental findings and on qualitative or quantitative methods; in their recourse to fundamental principles; and in how much they draw on the

> findings of other sciences. . . . Organizationally, science can be thought of as the collection of all of the different scientific fields, or content disciplines. From anthropology through zoology, there are dozens of such disciplines. . . . With respect to purpose and philosophy, however, all are equally scientific and together make up the same scientific endeavor. (AAAS 1989:25–26, 29)

Regarding the general principles, “Some important themes pervade science, mathematics, and technology and appear over and over again, whether we are looking at an ancient civilization, the human body, or a comet. They are ideas that transcend disciplinary boundaries and prove fruitful in explanation, in theory, in observation, and in design” (AAAS 1989:123). Accordingly, “Students should have the opportunity to learn the nature of the ‘scientific method’” (AAAS 1990:xii; also see AAAS 1993). That verdict is affirmed in official documents from the National Academy of Sciences (NAS 1995), the National Commission on Excellence in Education (NCEE 1983), the National Research Council of the NAS (NRC 1996, 1997, 1999, 2012), the National Science Foundation (NSF 1996), the National Science Teachers Association (NSTA 1995), and the counterparts of those organizations in many other nations (Matthews 2000:321–351). In all of these reports, scientific method holds a prominent position.

Science as a liberal art

An important difference between specialized techniques and general principles is that the former are discussed in essentially scientific and technical terms, whereas the latter inevitably involve a wider world of ideas. Accordingly, the central premise of the AAAS position paper on *The Liberal Art of Science* is extremely important: “Science is one of the liberal arts and . . . science must be taught as one of the liberal arts, which it unquestionably is” (AAAS 1990:xi).

Indeed, in antiquity, the liberal arts included some science. Grammar, logic, and rhetoric were in the lower division, the trivium; and arithmetic, geometry, astronomy, and music were in the higher division, the quadrivium. An early accretion was geology, and clearly the AAAS now includes all branches of contemporary science in the liberal art of science. A mosaic in a Cornell University chapel beautifully depicts the integration of all learning, with Philosophy the central figure flanked by Truth and Beauty (not shown) and the Arts and the Sciences to the right and left (Figure 1.4).

Many of the broad principles of scientific inquiry are not unique to science but also pervade rational inquiry more generally, as depicted in Figure 1.2. “All sciences share certain aspects of understanding—common perspectives that transcend disciplinary boundaries. Indeed, many of these fundamental values

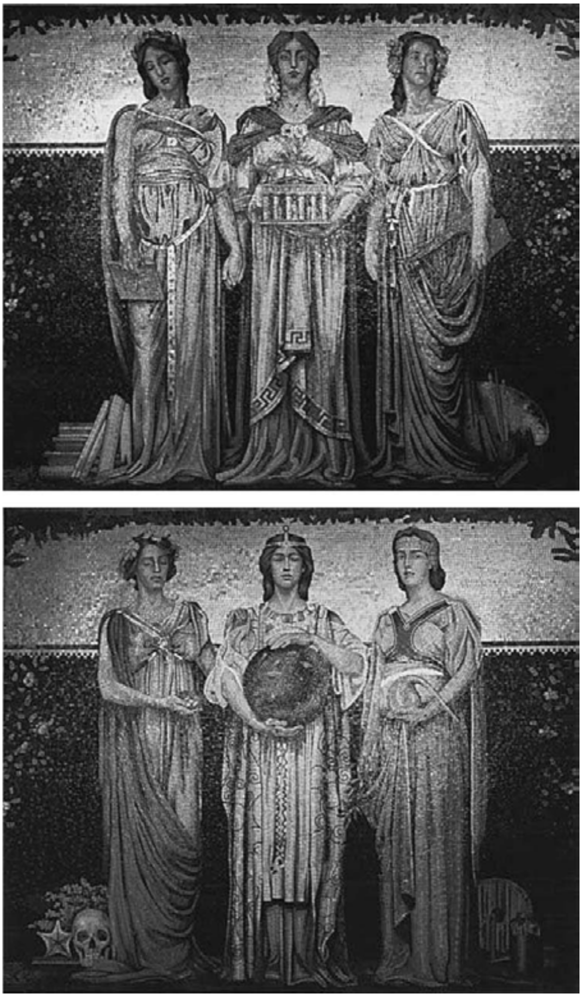

Figure 1.4 The Arts and the Sciences. The Arts are represented by Literature, Architecture, and Music, and the Sciences by Biology, Astronomy, and Physics. These details are from the mosaic *The Realm of Learning*, in Sage Chapel, Cornell University, that was designed by Ella Condie Lamb. (These photographs by Robert Barker of Cornell University Photography are reproduced with his kind permission.)

and aspects are also the province of the humanities, the fine and practical arts, and the social sciences" (AAAS 1990:xii; also see p. 11).

Furthermore, the continuity between science and common sense is respected, which implies productive applicability of scientific attitudes and thinking in daily life. "Although all sorts of imagination and thought may be used in coming up with hypotheses and theories, sooner or later scientific arguments must conform to the principles of logical reasoning—that is, to testing the validity of arguments by applying certain criteria of inference, demonstration, and common sense" (AAAS 1989:27). "There are . . . certain features of science that give it a distinctive character as a mode of inquiry. Although those features are especially characteristic of the work of professional scientists, everyone can exercise them in thinking scientifically about many matters of interest in everyday life" (AAAS 1989:26; also see AAAS 1990:16).

Because the general principles of science involve a wider world of ideas, many vital aspects cannot be understood satisfactorily by looking at science in isolation. Rather, they can be mastered properly only by seeing science in context, especially in philosophical and historical context. Therefore, this book's pursuit of the principles of scientific method sometimes ranges into discourse that has a distinctively philosophical or historical or sociological character. There is a natural and synergistic traffic of great ideas among the liberal arts, including science. The AAAS suggested several practical advantages from placing science within the liberal-arts tradition.

> Without the study of science and its relationships to other domains of knowledge, neither the intrinsic value of liberal education nor the practical benefits deriving from it can be achieved. Science, like the other liberal arts, contributes to the satisfaction of the human desire to know and understand. Moreover, a liberal education is the most practical education because it develops habits of mind that are essential for the conduct of the examined life. Ideally, a liberal education produces persons who are openminded and free from provincialism, dogma, preconception, and ideology; conscious of their opinions and judgments; reflective of their actions; and aware of their place in the social and natural worlds. The experience of learning science as a liberal art must be extended to all young people so that they can discover the sheer pleasure and intellectual satisfaction of understanding science. In this way, they will be empowered to participate more fully and fruitfully in their chosen professions and in civic affairs. . . . Education in science is more than the transmission of factual information: it must provide students with a knowledge base that enables them to educate themselves about the scientific and technological issues of their times; it must provide students with an understanding of the nature of science and its place in society; and it must provide them with an understanding of the methods and processes of scientific inquiry. (AAAS1990:xi–xii)

Matthews (1994:2) agreed: "Contributors to the liberal tradition believe that science taught . . . and informed by the history and philosophy of the subject can engender understanding of nature, the appreciation of beauty in both nature and science, and the awareness of ethical issues unveiled by scientific knowledge and created by scientific practice." He offered a specific example: "To teach Boyle's Law without reflection on what 'law' means in science, without considering what constitutes evidence for a law in science, and without attention to who Boyle was, when he lived, and what he did, is to teach in a truncated way. More can be made of the educational moment than merely teaching, or assisting students to discover that for a given gas at a constant temperature, pressure times volume is a constant" (Matthews 1994:3).

Indeed, concepts that are rich in philosophical content and meaning pervade science, such as rationality, truth, evidence, and cause. And deductive logic, probability theory, and other relevant topics have been addressed by both scientists and philosophers. Accordingly, an adequate understanding of science, for science and nonscience majors alike, must see science as one of the liberal arts. A humanities-rich vision of science surpasses a humanities-poor vision.

Certainly, the depictions by the AAAS of productive interactions between science and the other liberal arts are decidedly convivial and promising. But it must be acknowledged that science's recommended partners, the humanities, currently are in a state of tremendous turmoil and controversy.

With keen insight, Matthews (1994:9) discerned that there are "two broad camps" in the history and philosophy of science (HPS) literature, "those who appeal to HPS to support the teaching of science, and those who appeal to HPS to puncture the perceived arrogance and authority of science." This second camp stresses "the human face of science" and argues for pervasive "skepticism about scientific knowledge claims." Matthews's sensible reaction was to "embrace a number of the positions of the second group: science does have a human, cultural, and historical dimension, it is closely connected with philosophy, interests and values, and its knowledge claims are frequently tentative," and yet, "none of these admissions need lead to skepticism about the cognitive claims of science."

Given the profound internal controversies of the humanities, to suggest that science can gain strength by partnering with the humanities might seem like suggesting that a sober person seek support from a staggering drunk! But that would be an unfortunate overreaction. True, there are enough troubles in the humanities that a wanton relationship could weaken science. But much more importantly, there are enough insights and glories in the humanities that a discerning relationship can greatly strengthen science.

For the present, however, the foregoing rather cheerful and innocent account of science as a liberal art provides a fitting point of departure. Unquestionably and wonderfully, science is a liberal art.

Benefits and challenges

The expected benefits from studying scientific method are increased productivity and enhanced perspective. But, regrettably, for most university students, the current situation is challenging. Few science majors ever take a course in scientific method, logic, or the history and philosophy of science. "The hapless student is inevitably left to his or her own devices to pick up casually and

Elementary Scientific Method

- Hypothesis formulation
- Hypothesis testing
- Deductive and inductive logic
- Controlled experiments; replication and repeatability
- Interactions between data and theory
- Limits to science's domain

Figure 1.5 Typical topics in an elementary presentation of scientific method intended for college freshmen and sophomores. Introductory science texts often start with several pages on scientific method, discussing the formulation and testing of hypotheses, collection of data from controlled and replicated experiments, and so on. They are unlikely, however, to include any discussion of parsimony or any exploration of the history of scientific method beyond a passing mention of Aristotle.

randomly, from here and there, unorganized bits of the scientific method, as well as bits of *un*scientific methods" (Theocharis and Psimopoulos 1987). And the same is true for most science professors and professionals: "Ask a scientist what he conceives the scientific method to be, and he will adopt an expression that is at once solemn and shifty-eyed: solemn, because he feels he ought to declare an opinion; shifty-eyed, because he is wondering how to conceal the fact that he has no opinion to declare" (Medawar 1969:11).

The exposure of university students to science's principles is usually limited to the occasional science textbook that begins with brief remarks on scientific method. Figure 1.5 lists typical contents. But such an elementary view of scientific method is wholly inadequate at the university level for science and nonscience students alike.

What are the benefits from studying scientific method? The best answers have not come from scientists or philosophers but rather from science educators. They have conducted hundreds of careful empirical studies to characterize and quantify and compare the specific benefits that can result from learning the scientific method. Many of those studies have involved impressive sample sizes and carefully controlled experiments to quantify educational outcomes for students who either have or else have not received instruction in science's general principles. Because Chapter 13 will review the literature in science education, here only brief remarks without documentation will be presented, by way of anticipation.

(1) Better Comprehension. The specialized techniques and subject knowledge that so obviously make for productive scientists are better comprehended when the underlying principles of scientific method are understood. Giving adequate attention to both specialized knowledge and general principles creates a win-win situation.

(2) **Greater Adaptability.** It is facility with the general principles of science that contributes the most to a scientist's ability to be adaptable and to transfer knowledge and strategies from a familiar context to new ones. Adaptability is crucial as science and technology experience increasingly rapid and pervasive changes.

(3) **Greater Interest.** Most people find a humanities-rich version of science, with its wider perspective and big picture, much more engaging and interesting than a humanities-poor version. Including science's method, history, and philosophy in the science curriculum increases retention rates of students in the sciences.

(4) **More Realism.** An understanding of the scientific method leads to a realistic perspective on science's powers and limits. It also promotes balanced views of the complementary roles of the sciences and the humanities.

(5) **Better Researchers.** Researchers who master science's general principles gain productivity because they can make better decisions about whether or not to question an earlier interpretation of their data as a result of new evidence, whether or not there is a need to repeat an experiment, and where to look for other scientific work related to their project. They better assess how certain or accurate their conclusions are.

(6) **Better Teachers.** Teachers and professors who master science's general principles prove to be better at communicating science content. They are better at detecting and correcting students' prior mistaken notions and logic, and hence such teachers can better equip the next generation of scientists to be productive.

The facts of the case are clear, having been established by hundreds of empirical studies involving various age groups, nations, and science subjects: understanding the principles of scientific method does increase productivity and enhance perspective. Why? The most plausible explanation is simply that the thesis of this book is true: it really is the case that scientific methodology has two components, the general principles of scientific method and the research techniques of a chosen specialty, and the winning combination is strength in both.

Personal experience

Thus far, this introductory chapter has drawn on the insights of others, especially those of the AAAS and science educators, to support this book's thesis. But perhaps some readers would be interested in the personal experience that has prompted my interest in the principles of scientific method.

Figure 1.6 A soybean yield trial conducted in Aurora, New York. The soybean varieties here varied in terms of numerous traits. For example, the variety in the center foreground matured more quickly than the varieties to its left and right, making its leaves light yellow rather than dark green as the end of the growing season approached. Yield is a particularly important trait. (Reprinted from Gauch, 1992:3, with kind permission from Elsevier Science.)

My research specialty at Cornell University from 1970 to 2010 has been the statistical analysis of ecological and agricultural data. A special focus in this work has been agricultural yield trials. Worldwide, billions of dollars are spent annually to test various cultivars, fertilizers, insecticides, and so on. For instance, Figure 1.6 shows a soybean yield trial conducted to determine which cultivars perform best in various locations throughout the state of New York. The main objective of yield-trial research is to increase crop yields.

From studying the philosophy and method of science, but not from reading the agricultural literature, I came to realize that a statistical model can provide greater accuracy than can its raw data. As will be explained in Chapter 10 – on parsimony, which also is called simplicity or Ockham's razor – often statistical modeling increases accuracy as much as would collecting much more data. But the modeling costs merely a few seconds of computer time, whereas expanding data collection costs tens to hundreds of thousands of dollars in various instances, so this statistical gain in accuracy is spectacularly cost-effective. And greater accuracy improves decisions, increases repeatability, and accelerates progress.

The salient feature of that story is that the requisite statistical analyses and theory had been developed by 1955 and computers had become widely available to agronomists and breeders by 1970. However, no one had capitalized on that opportunity until Gauch (1988).

What has been the opportunity cost? Standard practices in agricultural research today are increasing the yields for most of the world's major crops by about 0.5% to 1.5% per year. A conservative estimate is that statistical models of yield-trial data often can support an additional increment of about 0.4% per year. Hence, for a typical case, if ordinary data analysis supports an average annual yield increase of 1%, whereas aggressive analysis supports 1.4%, then progress can be accelerated by another 40% simply by putting statistics to work. Regrettably, the opportunity cost for delaying that annual yield increment for a couple of decades equates to losing enough food for several hundreds of millions of persons, more than the population of North America.

What caused this reduction in crop productivity? Recalling the resource inventory in Figure 1.3, it was neither the lack of specialized research techniques nor the ability to easily perform billions of arithmetic steps. Rather, it was lack of understanding of parsimony, one of the general principles of scientific method. What was missing was the last of the critical resources listed in Figure 1.3. Method matters.

The larger issue that this experience raises is that many other scientific and technological specialties present us with tremendous opportunities that cannot be realized until some specialist in a given discipline masters and applies a critical general principle. Precisely because these are *general* principles, my suspicion is that my own experience is representative of what can be encountered in countless other specialties (Gauch 1993, 2006).

Furthermore, my own experience resonates with the AAAS (1990:xi) expectation that a broad vision of science as a liberal art is worthwhile for "the sheer pleasure and intellectual satisfaction of understanding science." I had a restless curiosity and deep interest regarding the basic principles of scientific thinking. But that spark of curiosity had received no stimulus or encouragement whatsoever from the courses and ideas presented in my university education.

While a graduate student at Cornell, I stumbled across a book by Arthur Burks not long after it was first published in 1963, which is now available in a newer edition (Burks 1977). He was a professor of both philosophy and computer science. His book was quite long, about 700 pages, and frequently was repetitious and tedious. However, it had the content that I had been seeking and had not yet found anywhere else. There at last I had found an intellectually satisfying account of the underlying principles and rationality of scientific thinking. That book immediately became a great favorite of mine. Subsequently, I sought and occasionally found additional books to nourish my ongoing interest in the principles of scientific method, most notably that by Jeffreys (1983), first published in 1961, and more recently Howson and Urbach (2006).

Thus, my interest in science's principles dates to about 1965. My motivation for that interest was – to echo the AAAS – the "sheer pleasure" that accompanies "the human desire to know and understand" (AAAS 1990:xi). Grasping the big ideas that are woven throughout the fabric of the entire scientific enterprise generates delight and confidence. However, the idea that mastery of those principles could also promote productivity did not awaken in my mind until a couple of decades later (Gauch 1988). Since then, my interest in these principles has been motivated by desires for both intellectual perspective and scientific productivity. During the 2000s, my interest in the general principles of scientific method has been further stimulated by co-teaching a course on scientific method with a colleague and thereby enjoying the intriguing and creative thinking of Cornell graduate and undergraduate students in science and nonscience majors.

Seven streams

Scientific method, as explored in the 14 chapters of this book, involves numerous topics. Readers wanting more information on a given topic should find the citations helpful. It may also be helpful to have an overview of the literature that bears on scientific method. The relevant literature is widely scattered and it has seven streams. These seven streams are complementary, so all seven are needed for a rich understanding of scientific method.

(1) Books on scientific method by scientists are the most obvious and directly relevant literature, although most are several decades old.
(2) Statistics provides the principal literature on a crucial component of scientific method: inductive logic (including experimental design, parameter estimation, data summary, and hypothesis testing).
(3) Philosophy of science provides profound insights on science.
(4) History of science provides essential perspective on science.
(5) Sociology of science reveals the human context of the scientific community.
(6) Science education is essential for the existence and flourishing of the scientific enterprise and for improving pedagogy. However, as seems quite natural and appropriate, these literatures primarily address the distinctive interests and purposes of philosophers, historians, sociologists, and educators. Nevertheless, there is a fraction of these literatures that can serve a different purpose, helping scientists to become better scientists. That is the fraction selectively emphasized in my citations to and quotations from these four literature streams.
(7) Last and immensely valuable, there are position papers on science from the AAAS, NAS, NSF, and other leading scientific organizations, as well as their counterparts in many other nations.

The important roles of position papers and science education standards in this book merits explanation. The nature of scientific method and the reliability of scientific findings have been debated for centuries, including hot debates in recent decades, as Chapter 4 documents. More broadly, the status of human knowledge has been contested without interruption from antiquity to the present, as Chapters 2 and 3 explain. Multiple positions increase the complexity of a book on scientific method, unavoidably. But against this complex backdrop of multiple positions, these prominent position papers describe, distinguish, and privilege one particular position as being the mainstream position. As will be evident from the historical material in this book (as well as in these position papers), many of the main features of scientific method in its contemporary, mainstream manifestation have been stable features of science for several centuries, or even as long as two millennia for some key ideas.

My intention as an author on scientific method, which I want to make known to my readers explicitly and clearly in this first chapter, is to align with mainstream science. Not only does this represent my own personal convictions, it also best serves the needs of both the scientific community and the general public. Mainstream science is ideal for developing technology, appreciating nature, and interacting with the humanities in a fruitful manner.

The principal position papers and education standards engaged here are *Science for All Americans* (AAAS 1989); *The Liberal Art of Science* (AAAS 1990); *Reshaping the Graduate Education of Scientists and Engineers* (NAS 1995); *National Science Education Standards* (NRC 1996); *Shaping the Future: New Expectations for Undergraduate Education in Science, Mathematics, Engineering, and Technology* (NSF 1996); *Transforming Undergraduate Education in Science, Mathematics, Engineering, and Technology* (NRC 1999); *On Being a Scientist: A Guide to Responsible Conduct in Research* (NAS 2009); and *A Framework for K–12 Education: Practices, Crosscutting Concepts, and Core Ideas* (NRC 2012). These careful documents involved hundreds of outstanding scientists and scholars as contributors and reviewers, who worked through drafts over several years.

Listed here are several books from each of these seven streams that express a diversity of views on science and scientific method. Exemplary books on scientific method include Nash (1963), Burks (1977), and Derry (1999), with Carey (2012) an admirable book at a somewhat more elementary level. Exceptional books on statistics include Berger (1985), Gelman et al. (2004), Taper and Lele (2004), Howson and Urbach (2006), Robert (2007), and Hoff (2009). Philosophical perspectives on science are addressed by Trigg (1993), Godfrey-Smith (2003), Nola and Sankey (2007), Gimbel (2011), and Rosenberg (2012); historical perspectives by Gower (1997), Losee (2001), McClellan and Dorn (2006), and Lindberg (2007); sociological perspectives by Merton (1973), Merton and Sztompka (1996), and Stehr and Meja (2005); and educational perspectives by Matthews (1994), McComas (1998), Hodson (2009), and Niaz (2011). Finally, the scientific community would benefit from greater awareness of the position papers on science, already cited herein, from the AAAS, NAS, and NSF.

Historical and future outlook

Despite the unanimous recommendation from the AAAS and many other leading scientific organizations in many nations that scientific method be emphasized in the science curriculum, the current situation at the university level is one of pervasive neglect. Despite the AAAS verdict that science unquestionably is one of the liberal arts, in recent decades, this has not been generally and clearly appreciated. Consequently, turning the AAAS vision into reality will require some effort: "In spite of the importance of science and the ubiquity of its applications, science has not been integrated adequately into the totality of human experience. . . . Understanding science and its influence on society and the natural world will require a vast reform in science education from preschool to university" (AAAS 1990:xi). What went wrong?

To understand the huge discrepancy between the AAAS vision of humanities-rich science and the current reality of humanities-poor science, some rudimentary historical perspective is needed. By AD 500, the classical liberal arts had already become well codified in the trivium and quadrivium, which included some science. Then, around 1200, and coincident with the founding of the earliest universities, there was a great influx of knowledge into Western Europe.

Around 1850, at about the time when many of the great universities in the USA and elsewhere beyond Europe were being founded, there were two revealing developments: invention of the new word "scientist" and acquisition of a new meaning for the word "science." The term "scientist" was coined in 1834 by members of the British Association for the Advancement of Science to describe students of nature, by analogy with the previously existing term "artist." Subsequently, that new word was established securely in 1840 through William Whewell's popular writings. Somewhat later, in the 1860s, the *Oxford English Dictionary* (OED) recognized that "science" had come to have a new meaning as "physical and experimental science, to the exclusion of theological and metaphysical," and the 1987 supplement to the OED remarked that "this is now the dominant sense in ordinary use" (http://dictionary.oed.com). Those new or modified words certified science's coming of age, with its own independent intellectual identity. Increasingly since 1850, science has also had its own institutional identity.

The rift between the sciences and the humanities reached its peak around the 1920s and 1930s, with a prevailing conception of science that discounted human factors in science and intentionally disdained philosophy, especially metaphysics. A turning point came in 1959 with the publication of two books destined to have enormous influence: Sir Karl Popper's *The Logic of Scientific*

Discovery called for a human-sized account of science, with significant philosophical, historical, and sociological content (Popper 1968); and C. P. Snow's *The Two Cultures and the Scientific Revolution* drew attention to the divide between the sciences and the humanities with its resulting lamentable intellectual fragmentation (Snow 1993). So the connection between science and the humanities has varied somewhat during the twentieth century, but on the whole there has been a considerable rift between the two cultures.

For twenty-two centuries, from Aristotle until the twentieth century, it was the universal practice of the scientific community to produce scholars who understood both philosophy and science. To use a term fittingly applied to Einstein by Schilpp (1951), they were philosopher-scientists. Einstein rightly insisted that "Science without Epistemology is – in so far as it is thinkable at all – primitive and muddled" (Rosenthal-Schneider 1980:27). But most contemporary scientists receive meager training in the history and philosophy of science, epistemology, the principles of scientific method, and logic. It would be beneficial for the scientific community to return to the venerable tradition, which served previous generations well, of producing philosopher-scientists.

The twentieth century has been the one and only century in science's rich history to have produced mostly scientists rather than philosopher-scientists. Consequently, many contemporary scientists cannot defend science's rationality and credibility from various intellectual attacks and they cannot optimize the methods and productivity of their own research programs. Weakness in scientific method is costly, wasting research dollars, compromising competitive advantages, delaying scientific discoveries and technological advances, and reducing the sheer intellectual pleasure that could be derived from a humanities-rich version of science.

Summary

Science and technology have immense cultural and economic significance. Scientific method is the gateway into scientific discoveries that in turn prompt technological advances and cultural influences. Science is best understood in a humanities-rich version that perceives science as a liberal art.

The thesis of this book is that there exist general principles of scientific method that are applicable across all of the sciences, undergird science's rationality, and greatly influence science's productivity and perspective. These general methodological principles include deductive and inductive logic, probability, parsimony, and hypothesis testing as well as science's presuppositions, limitations, and ethics. The implicit contrast is with specialized techniques that occur only in some sciences or applications. The winning combination for scientists is strength in both. Neither basic principles nor research techniques can substitute for one another. This winning combination increases productivity and enhances perspective.

On five counts, this thesis merits serious consideration. First, that science has a scientific method with general principles and that these principles can benefit scientists is the official, considered view of the AAAS (and the NAS, NRC, NSF, and other major scientific organizations in the United States, as well as similar entities in numerous other nations). Second, science's basic concepts and methods – such as rationality, truth, deductive and inductive logic, and parsimony – interconnect with philosophy, history, and other humanities, so the official view of the AAAS is compelling that a humanities-rich version of science as a liberal art stimulates clarity and perspective. Third, science educators have demonstrated in hundreds of empirical studies, often involving sizable samples and controlled experiments, that learning science's general principles can benefit students and scientists in several specific, quantifiable, important respects. Fourth, my own research experience, primarily involving agricultural yield-trial experiments, demonstrates the practical value of a particular principle of scientific method, namely parsimony. Fifth and finally, prior to the twentieth century, for twenty-two centuries following Aristotle, the customary practice of the scientific community, which served it well, had been to produce philosopher-scientists.

This book's message is that a disproportionately large share of future advances in science and technology will come from those researchers who have mastered their specialties like everyone else but who also have mastered the basics of science's philosophy and method. Also, philosopher-scientists will be prominent among those scholars providing the best reflections on science's rationality, relationship with the humanities, powers and limits, and roles in culture and life.

Study questions

(1) Would you suspect that many other seemingly simple and ordinary products, besides a loaf of bread or cup of rice, incorporate extensive scientific research and technological development? Can you give a specific example or two?

(2) Characterize the distinction between specialized techniques and general principles of scientific method. Where does or should the latter appear in the science curriculum, particularly for undergraduates and graduates in science?

(3) How do you react to the AAAS position that science is one of the liberal arts, unquestionably? Is this position familiar or foreign in your own university education? What are some clear implications and potential benefits from a humanities-rich version of science?

(4) What benefits from studying scientific method in particular, or the nature of science more generally, have science educators demonstrated with hundreds of empirical studies?

(5) If you are in the sciences, which specific weaknesses within your own specialty might plausibly be attributed to an inadequate understanding of scientific method? Or if you are in the humanities, have you been satisfied with prevalent characterizations of science's role and significance?

2

Four bold claims

This is the first of five chapters (2–6) directed mainly at this book's purpose of cultivating a humanities-rich perspective on science. The following five chapters (7–11) are directed mainly at this book's other purpose of increasing scientific productivity.

Consider a familiar scientific fact: water is composed of hydrogen and oxygen, having the chemical formula H_2O. The objective of this and the following chapter is to comprehend exactly what claims science makes for such findings. Accordingly, this chapter explicates the concepts of rationality, truth, objectivity, and realism. Mainstream science uses these four concepts incessantly, although usually implicitly, so the philosophical literature on these concepts can enrich scientists' understanding of their own craft. The next chapter explores the historical development of the concept of truth as applied to knowledge about the physical world, from Aristotle to the present. Finally, toward the end of the next chapter, additional scientific information will be presented to complete this story about science's rational, true, objective, and realistic knowledge that water is H_2O. Science worthy of the name must attend not only to facts about electrons, bacteria, humans, and galaxies but also to concepts of rationality, truth, objectivity, and realism.

Rationality

Rationality is good reasoning. The traditional concept of rationality in philosophy, which is also singularly appropriate in science, is that reason holds a double office: regulating belief and guiding action. Rational beliefs have appropriate evidence and reasons that support their truth, and rational actions promote what is good. Rational persons seek true beliefs to guide good actions. "Pieces of behaviour, beliefs, arguments, policies, and other exercises of the human mind may all be described as rational. To accept something as rational is to accept it as making sense, as appropriate, or required, or in accordance with some acknowledged goal, such as aiming at truth or aiming at the good" (Blackburn 1994:319).

Scientific inquiry involves imagination, insight, creativity, and sometimes luck, but in no way does that negate science also involving good reasoning. "Although all sorts of imagination and thought may be used in coming up with hypotheses and theories, sooner or later scientific arguments must conform to the principles of logical reasoning—that is, to testing the validity of arguments by applying certain criteria of inference, demonstration, and common sense" (AAAS 1989:27).

Of science's four bold claims, rationality is discussed first because it is so integral to this book's topic, the scientific method. Although beliefs, persons, and other things can be the objects of a claim of rationality, the principal target here is method. Method precedes and produces results, so claims of rationality for science's conclusions are derivative from more strategic claims of rationality for science's method. Rational methods produce rational beliefs.

A claim of rational knowledge follows this formula: I hold belief *X* for reasons *R* with level of confidence *C*, where assertion of *X* is within the domain of competence of method *M* that accesses the relevant aspects of reality. The first-order belief *X* is accompanied by a second-order belief that assesses the strength of the reasons *R* and hence the appropriate level of confidence *C*, which may range from low probability to high probability to certainty. Besides supporting belief *X*, some effort may also be directed at discrediting various alternative beliefs, *Y* and *Z*. Lastly, the reasons and evidence have meaning and force from a third-order appeal to an appropriate method *M* that accesses the aspects of reality that are relevant for an inquiry into *X*. For example, the scientific method is directed at physical reality, and its domain of competence includes reaching a confident belief, based on compelling evidence, about the composition of table salt.

This business of giving reasons *R* for belief *X* must eventually stop somewhere, however, so not quite all knowledge claims can follow this formula. Rather, some must follow an alternative formula: I hold belief *X* because of presuppositions *P*. This is a story, however, that is better deferred to Chapter 5. The important story at present is just that methods underlie reasons, which in turn underlie beliefs and truth claims.

Reason's double office, of regulating belief and guiding action, means that true belief goes with good action. When belief and action do not agree, which is a moral problem rather than an intellectual problem, the result is insincerity and hypocrisy. When reason is wrongfully demoted to the single office of only regulating belief, thus severing belief from action, the inevitable consequence is sickly beliefs deliberately shielded from reality.

The traditional opponent of reason was passion, as in Plato's picture of reason as a charioteer commanding unruly passions as the horses. So a rational person is one who sincerely intends to believe the truth, even if occasionally strong desires go against reason's dictates.

The claim to be defended here, that science is rational, should not be misconstrued as the different and imperialistic claim that only science is rational. To the contrary, science is a form of rationality applied to physical objects, and science flourishes best when integrated with additional forms of rationality, including common sense and philosophy. "The method of natural science is not the sole and universal rational way of reaching truth; it is one version of rational method, adapted to a particular set of truths" (Caldin 1949:134).

Likewise, the claim to be defended here, that science is rational, should not be conflated with the different and indefensible claim that science is always beneficial. It is unfair to deem that atomic weapons and carcinogenic insecticides count against science's rationality. Obviously, the simple truth is that knowledge of physical reality can be used for good or for ill. Science in the mind is like a stick in the hand: it increases one's ability to work one's will, regardless of whether that will is good or bad, informed or careless.

Truth

Truth is a property of a statement, namely, that the statement corresponds with reality. This correspondence theory of truth goes back to Aristotle, who wrote that "To say of what is that it is not, or of what is not that it is, is false, while to say of what is that it is, and of what is not that it is not, is true" (McKeon 1941:749). This definition has three components: a statement declaring something about the world, the actual state of the world, and the relationship of correspondence between the statement and the world. For example, if I say "This glass contains orange juice" and the state of affairs is that this glass does contain orange juice, then this statement corresponds with the world and hence it is true. But if I say that it contains orange juice when it does not, or that it does not contain orange juice when it does, then such statements are false. Truth claims may be expressed with various levels of confidence, such as "I am certain that 'Table salt is sodium chloride' is true" or "The doctors believe that 'The tumor is not malignant' with 90% confidence" or "There is a 95% probability that the sample's true mass is within the interval 1,072 ± 3 grams." Figure 2.1 depicts Aristotle's correspondence concept of truth.

The correspondence theory of truth grants reality priority over beliefs: "the facts about the world determine the truth of statements, but the converse is not true," and this asymmetry is nothing less than "a defining feature of truth about objective reality" (Irwin 1988:5). "In claiming that truth is correspondence to the facts, Aristotle accepts a biconditional; it is true that *p* if and only if *p*. But he finds the mere biconditional inadequate for the asymmetry and natural priority he finds in the relation of correspondence; this asymmetry is to be captured

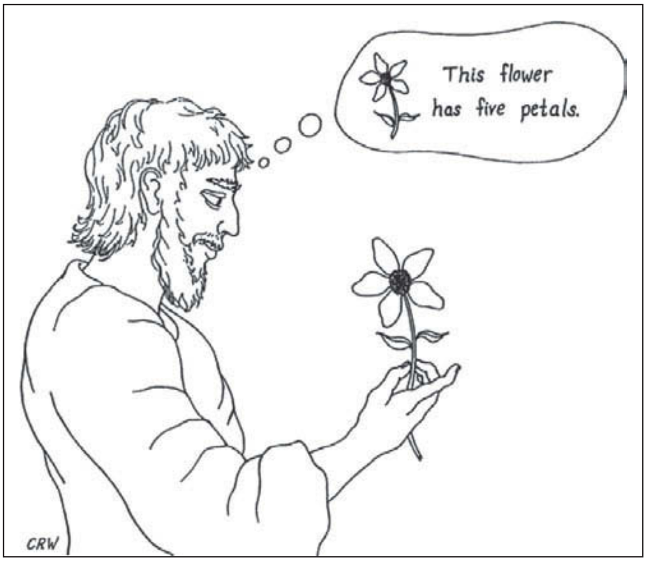

Figure 2.1 **The correspondence concept of truth, with priority of nature over belief. Here the state of nature is a flower with five petals, and the person's belief is that the flower has five petals, so nature and belief correspond and, consequently this brilliant scientist's belief is true. It is the flower's petals, not the scientist's beliefs, that control the right answer. Beliefs corresponding with reality are true. (This drawing by Carl R. Whittaker is reproduced with his kind permission.)**

in causal or explanatory terms" (Irwin 1988:5–6). Again, "Truth is accuracy or representation of an independent world – a world that, while it includes us and our acts of representing it, decides the accuracy of our representations of it and is not constructed by them" (Leplin 1997:29).

In the correspondence definition of truth, notice that the bearers of truth are statements, not persons. Persons are the bearers of statements, but statements are the bearers of truth. Accordingly, truth is not affected by who does or does not say it.

For better or for worse, philosophers have proposed numerous definitions of truth besides the correspondence theory advocated here. What is valid in those other definitions is best regarded as routine elaboration of the correspondence definition, which alone can serve science as the core concept of truth.

For example, the coherence theory says that truth consists in coherence (agreement) among a set of beliefs. The valid element here is that coherence is crucial. Thus, if I say that "Table salt is sodium chloride" and at the same time also blithely voice the contrary that "Table salt is not sodium chloride," then

I lose credit for this first statement because of the incoherence and insincerity caused by the second statement. Likewise, to be either true or false, a statement must at least make sense; "big it run brown" is neither true nor false, but nonsense.

For another example, the pragmatic theory of truth says that the truth is what works. The valid element here is that truth does have practical value for doing business with reality. Thus, if your doctor puts you on a low-sodium diet, then there is practical value in understanding the truth that table salt is sodium chloride. Again, reason holds the double office of regulating belief and guiding action. The danger here would be to let pragmatic actions replace true beliefs, rather than complement them, in a theory of truth.

When the correspondence, coherence, pragmatic, and other theories of truth are all considered seriously and respected equally, in practice none of them wins the day. Rather, the only winner would seem to be a "mystification theory" of truth, saying that it is beyond humans to understand or define truth. Is this *your* theory of truth? There is a simple test: your mother asks this question: "Did you eat the last cookie? Now tell the truth!" If you are capable of answering that question, then someone else may be mystified about what truth is, but you are not. The mystification theory of truth is just bad philosophy.

The definition of truth is one easy little bit of philosophy that scientists must get straight before their enterprise can make meaningful claims. A true statement corresponds with reality. A characteristic feature of antiscientific and postmodern views is to place the word "truth" in scare quotes, or else proudly to avoid this word altogether. Indeed, *every* kind and variety of antiscientific philosophy has, as an essential part of its machinery, a defective notion of truth that assists in the sad task of rendering truth elusive. Scientists must take warning from the words of Leplin (1997:28) that "All manner of truth-surrogates have been proposed" by some philosophers "as what science *really* aims for." Scientists must reject all substitutes.

The definition of truth plays the important role of making scientific hypotheses meaningful even before collecting and analyzing data to test it. For example, the hypothesis that "a carbon atom contains nine protons" is meaningful precisely because it is understood as an attempt at truth, although in this particular case, experimental data would result in rejection of that hypothesis.

Truth is guarded by science's insistent demand for evidence. "Sooner or later, the validity of scientific claims is settled by referring to observations of phenomena. . . . When faced with a claim that something is true, scientists respond by asking what evidence supports it" (AAAS 1989:26, 28).

Because true statements correspond with objective reality, a theory of truth should be complemented by theories of objectivity and realism. Accordingly, the next two sections discuss these two related concepts.

Objectivity

In its primary usage, the concept of objectivity often appears in adjectival form as objective belief, objective knowledge, or objective truth. This concept is complex and somewhat subtle, having three interrelated aspects. Objective knowledge is about an object, rather than a subject or knower; it is achievable by the exercise of ordinary endowments common to all humans, so agreement among persons is possible; and it is not subverted and undone by differences between persons in their worldview commitments, at least for nearly all worldviews.

The first of the three interrelated aspects of objectivity is that objective knowledge is about an object. The AAAS characterizes science beautifully in the simple words that "science is the art of interrogating nature" with "commitment to understanding the natural world" (AAAS 1990:17). For example, "Table salt is sodium chloride" expresses an objective claim about an object, table salt, while expressing nothing about persons who do or do not hold this belief. Because objective beliefs are about objects themselves, not the persons expressing beliefs, the truth or falsity of an objective belief is determined by the belief's object, such as table salt. This thinking reflects and respects the correspondence theory of truth and its priority of reality over beliefs.

In Aristotle's terms, an objective truth about nature is a truth "known by nature," meaning that it expresses a real feature of the physical world, not just an opinion suited to our cognitive capacities or our questionable theories (Irwin 1988:5). Indeed, "As one physicist remarked, physics is about how atoms appear to atoms," and "in science the ultimate dissenting voice is nature itself, and that is a voice which even an entrenched scientific establishment cannot silence for ever" (O'Hear 1989:229, 215). Science's goal is "observer-independent truths about a world independent of us," and "The truths science attempts to reveal about atoms and the solar system and even about microbes and bacteria would still be true even if human beings had never existed" (O'Hear 1989:231, 6).

The second aspect of objectivity is that objective knowledge is achievable by the exercise of ordinary endowments common to all humans, so agreement among persons is possible. Consequently, science's claims are public and verifiable. "Men and women of all ethnic and national backgrounds participate in science and its applications.... Because of the social nature of science, the dissemination of scientific information is crucial to its progress" (AAAS 1989:28–29). The link between objective truth and inter-subjective agreement is so strong that the former is difficult to defend when the latter fails.

The third and final aspect of objectivity is immunity to worldview differences. A major reason why science is respected is that it cuts across political, cultural, and religious divisions.

> The impartiality of nature to our feelings, beliefs, and desires means that the work of testing and developing scientific theories is insensitive to the ideological background of

> individual scientists.... [Indeed,] science does cut through political ideology, because its theories are about nature, and made true or false by a nonpartisan nature, whatever the race or beliefs of their inventor, and however they conform or fail to conform to political or religious opinion.... There is no such thing as British science, or Catholic science, or Communist science, though there are Britons, Catholics, and Communists who are scientists, and who should, as scientists, be able to communicate fully with each other. (O'Hear 1989:6–7, 2, 8)

There is humility, openness, and generosity of spirit in realizing that not only your own worldview supports science, but also most other worldviews allow science to make sense. But having just emphasized that science rises above worldview divisions, on balance it must also be said that this immunity to worldview differences is substantial and satisfactory, but not total. Although held by only a small minority of the world's population, there are some worldviews that are so deeply skeptical or relativistic that they do not and cannot support anything recognizable as science's ordinary claims. And those worldview commitments have a deeper role and greater influence than any and all of science's evidence. But that is a story better told in Chapter 5, on science's presuppositions. For the present, it suffices to acknowledge that science is for almost everyone, but not quite everyone.

"Objectivity" also has a secondary usage that applies to persons rather than to beliefs. When formulating their beliefs, objective persons are willing to allow facts and truth to overrule prejudices and desires. Science "forbids a man to sink into himself and his selfish claims, and shifts the centre of interest from within himself to outside" (Caldin 1949:135–136). Objective inquirers welcome truth.

Furthermore, it must be emphasized that objective knowledge is claimed or possessed by human subjects, for otherwise, unrealistic and indefensible versions of objectivity would emerge. Scientists, as human beings, "must inevitably see the universe from a centre lying within ourselves and speak about it in terms of a human language shaped by the exigencies of human intercourse. Any attempt rigorously to eliminate our human perspective from our picture of the world must lead to absurdity" (Polanyi 1962:3). Objective knowledge that is shared among numerous persons gives science a convivial social aspect, the scientific community.

> Articulate systems which foster and satisfy an intellectual passion can survive only with the support of a society which respects the values affirmed by these passions.... [Thus,] our adherence to the truth can be seen to imply our adherence to a society which respects the truth, and which we trust to respect it. Love of truth and of intellectual values in general will... reappear as the love of the kind of society which fosters these values, and submission to intellectual standards will be seen to imply participation in a society which accepts the cultural obligation to serve these standards. (Polanyi 1962:203)

But having acknowledged the subjective and social aspects of objectivity, a grave pathology develops if subjectivity supplants rather than complements objectivity. Such elevation of the knower over the known actually demeans the personal aspect of knowing because it leaves scientists with nothing for their beliefs to be about. That outcome illustrates the principle that every excess becomes its own punishment. Any attempt to eliminate physical objects from science's picture of the world and any attempt to eliminate human persons from science's picture of the world must alike lead to absurdity.

Realism

Realism, as regards the physical world, is the philosophical theory that both human thoughts and independent physical objects exist and that human endowments render the physical world substantially intelligible and reliably known. Scientific realism embodies the claim that the scientific method provides rational access to physical reality, generating much objective knowledge. Realistic beliefs correspond with reality. Realistic persons welcome reality.

> We are trying to refer to reality whenever we say what we think exists. Some may wish to talk of God, and others may think matter is the ultimate reality. Nevertheless, we all talk about tables and chairs, cats and rabbits. They exist, and are real, and do not just depend in some way on our thought for their existence. . . . Man himself is part of reality, and causally interacts with other segments of reality. He can change things, and even sometimes control them. He does not decide what is real and what is not, but he can make up his mind what he thinks real. This is the pursuit of truth. Man's attempt to make true assertions about the self-subsistent world of which he is a part may not always be successful, and may not always prove easy or straightforward. The repudiation of it as a goal would not only destroy science, but would make human intellectual activity totally pointless. (Trigg 1980:200)

Reality does not come in degrees because something either does or does not exist. Thus, one little potato is fully as real as is the entire universe. It is not as big, not as important, and not as enduring, but it is just as real. Likewise, one little potato that exists fleetingly now is completely real regardless of whatever ultimate reality may be invoked to explain or cause or sustain its existence. Science claims to deal with reality. But, clearly, some humility is in order regarding the extent of science's reach. Scientists can agree that a little potato is real even while there is disagreement, uncertainty, or even ignorance about the deep philosophical or physical explanation of its existence.

Common-sense belief in reality is practically universal. For example, a child may say "I am patting my cat." What does this mean? Manifestly, the philosophical story, too obvious to be elaborated in ordinary discourse, is that the child feels and sees and enjoys the cat by virtue of having hands and eyes and brain in close proximity to the furry quadruped. And science's realism is the same. “The simple and unscientific man’s belief in reality is fundamentally the same as that of the scientist” (Max Born, quoted by Nash 1963:29). On the basis of numerous conversations, Rosenthal-Schneider (1980:30) summarized Einstein’s view: “Correspondence to the real physical universe, to nature, was for him the essential feature, the only one which would give ‘truth-value’ to any theory.”

The opposite of realism is antirealism, in any of its many variants. Recall from this section’s opening definition that realism combines two tenets: the existence of objects and minds, and the intelligibility of objects to minds. Idealism denies the first tenet. It says that only minds exist and that “objects” are just illusions imagined by minds. Constructivism claims that the physical world is a projection of the mind, so we construct rather than discover reality. Instrumentalism denies that external physical objects should be the targets of our truth claims, substituting internal perceptions and thoughts as the material for analysis. Skepticism denies the second tenet. It does not deny that the physical world exists, but it denies that we do have or could have any reliable knowledge about the physical world. Relativism accepts personal truth-for-me but not public truth-for-everyone, so there is no objective and shared knowledge about the world such as the scientific community claims.

Ordinary science is so thoroughly tied to realism that realism’s competitors seem to scientists to be somewhat like the philosophical joke expressed well in a little story by Wittgenstein: “I am sitting with a philosopher in the garden; he says again and again ‘I know that that’s a tree’, pointing to a tree that is near us. Someone else arrives and hears this, and I tell him: ‘This fellow isn’t insane. We are only doing philosophy’” (Anscombe and von Wright 1969:61e). Without realism, ordinary science perishes.

The full force of science’s claims results from the joint assertion of all four: rationality, truth, objectivity, and realism. Science claims to have a rational method that provides humans with objective truth about physical reality. The meanings of science’s four claims are reviewed in Figure 2.2.

Science and common sense

The choice of a suitable strategy for defending science’s four bold claims in subsequent chapters is greatly affected by the relationship between science and common sense. However, for better or for worse, that relationship is highly contentious. There are two basic choices. Science can be seen as a refinement of common sense, so the defense of science’s four bold claims begins with an appeal to common sense. Or, science can be seen as an unnatural and counter-intuitive enterprise relative to simplistic common sense, so science’s defense must locate other resources. As exemplars of these two choices, this section considers Nash (1963) and Wolpert (1993).

Science's Four Claims

Rationality
Rational methods of inquiry use reason and evidence correctly to achieve substantial and specified success in finding truth, and rational actions use rational and true beliefs to guide good actions.

Truth
True statements correspond with reality:

Correspondence
External Physical World ← Internal Mental World
of Objects and Events → of Perceptions and Beliefs

Objectivity
Objective beliefs concern external physical objects; they can be tested and verified so that consensus will emerge among knowledgeable persons; and they do not depend on controversial presuppositions or special worldviews.

Realism
Realism is correspondence of human thoughts with an external and independent reality, including physical objects.

Figure 2.2 Science's claims of rationality, truth, objectivity, and realism.

The Nature of the Natural Sciences by Nash (1963) has a first chapter titled "Common Sense (and Science)" and a second chapter titled "Science (and Common Sense)." Nash began: "Science is a way of looking at the world. There are, of course, other ways. The man of common sense sees the world in his own way. So does the artist, the philosopher, the theologian. The view of the scientist, if at all unique, is characterized by its heavy involvement of elements drawn from all the others" (page 3). But, given those basic elements, the scientist then "seeks a higher unity, a deeper understanding, unknown to common sense" (page 3). He added: "Though between science and common sense there exist dissimilarities we must not (and will not) overlook, the strong similarities between them establish for us a point of departure. Seeking to understand science, we begin by trying to understand the nature of common sense" (page 4). Nash recommended that we follow Einstein, whom he quoted as saying:

> The whole of science is nothing more than a refinement of everyday thinking. It is for this reason that the critical thinking of the physicist cannot possibly be restricted to the examination of the concepts of his own specific field. He cannot proceed without considering critically a much more difficult problem, the problem of analyzing the nature of everyday thinking. (Albert Einstein, quoted in Nash 1963:4)

By contrast, *The Unnatural Nature of Science* by Wolpert (1993) has a first chapter titled “Unnatural Thoughts” that gives many examples of scientific discoveries that seem unnatural from the perspective of common sense. For instance, objects move in different paths than common sense leads most people to expect, white light is composed of a mixture of different colors, and correct probability judgments are often counter-intuitive. He expressed his perspective concisely:

> The central theme presented in this book is that many of the misunderstandings about the nature of science might be corrected once it is realized just how ‘unnatural’ science is. I will argue that science involves a special mode of thought and is unnatural for two main reasons. . . . Firstly, the world just is not constructed on a common-sensical basis. This means that ‘natural’ thinking – ordinary, day-to-day common sense – will never give an understanding about the nature of science. Scientific ideas are, with rare exceptions, counter-intuitive: they cannot be acquired by simple inspection of phenomena and are often outside everyday experience. Secondly, doing science requires a conscious awareness of the pitfalls of ‘natural’ thinking. For common sense is prone to error when applied to problems requiring rigorous and quantitative thinking; lay theories are highly unreliable. (Wolpert 1993:xi–xii)

Upon encountering these opposing views, the first necessity is to recognize that any two things are partly similar and partly dissimilar. For instance, a bird and a stone are similar with respect to being physical objects, but they are dissimilar with respect to being alive. The same holds for science and common sense, being similar in some respects and dissimilar in others. Given that simple insight, this book can accommodate Nash and Wolpert alike.

On the one hand, the similarity of science and common sense is asserted here with respect to two absolutely crucial matters. First, both have the same concept of truth. When a child says “I ate three cookies” and a scientist says “Table salt is NaCl,” the same concept and criterion of truth is at work, correspondence of a statement with reality. The concept of truth did not originate with the emergence of science! Rather, all four of science’s bold claims – rationality, truth, objectivity, and realism – have a continuity with those claims in common sense. Second, as will be elaborated in Chapter 5, science’s presuppositions of a real and comprehensible world, which are indispensable for mainstream science, are best legitimated by an appeal to common sense. One might suppose that a viable or preferable alternative would be an appeal to philosophy, but philosophy is in the same position as science as regards its dependence on common sense for these presuppositions.

On the other hand, the dissimilarity of science and common sense is asserted here with respect to the more advanced and exacting methods of science and the frequently surprising and bizarre findings of science. That scientific method is demanding and sometimes even counter-intuitive is precisely why books like this are needed! And scientific findings in everything from quantum mechanics to biology to cosmology are amazing and decidedly beyond common sense's reach.

Accordingly, a proper understanding of science must hold in tension both the similarities and dissimilarities between science and common sense. For example, consider the common-sense view that time passes at a constant rate, which has been overturned by the surprising view in Einstein's relativity theory that time passes at different rates depending on an object's speed relative to a given observer. Those different rates can actually be measured for satellites and other fast-moving objects by using extremely accurate clocks, and these measurements agree precisely with theory. Nevertheless, the strange world of relativity theory or quantum mechanics is not detached from the humdrum world of common sense because a scientist looks at a clock or measures a speed or whatever, and those appeals to empirical evidence necessarily require presuppositions about a real and comprehensible world that were best legitimated by a previous appeal to common sense. Furthermore, within the common-sense realm of ordinary speeds and ordinary clocks, relativity confirms, rather than contradicts, the common-sense perception that time always passes at a constant rate. No relativistic corrections are needed in a baseball park.

Science and common sense are partly dissimilar and partly similar. Scientific method, as compared to common-sense thinking, has complicated evidence and advanced logic supporting remarkable conclusions, but it also has identical presuppositions and shared concepts such as rationality and truth.

Summary

Science's four traditional claims are rationality, truth, objectivity, and realism. This chapter explores these four bold claims, drawing on the relevant philosophical literature that tends to be unfamiliar to scientists.

Rationality is good reasoning. Reason holds the double office of regulating belief and guiding action. Rational methods of inquiry, including scientific method, use reason and evidence correctly to achieve substantial and specified success in finding truth, and rational actions use rational and true beliefs to guide good actions.

Truth consists of correspondence between a statement and the actual state of affairs. This correspondence theory of truth presumes and subsumes the coherence theory requiring agreement among a set of beliefs, and it implies and confirms the pragmatic theory saying that truth promotes business with reality in a manner unmatched by ignorance and error. Nevertheless, the principal and essential concept is that of correspondence. The definition of truth is one very simple bit of philosophy: true statements correspond with reality. The real challenge is not the definition of truth but rather the implementation of effective methods for sorting true from false statements.

Objectivity has three interrelated aspects. Principally, objective beliefs are about objects themselves, rather than persons expressing beliefs, so the truth or falsity of an objective belief is determined by the belief's object, such as table salt. Secondly, objective knowledge is attainable by the exercise of ordinary endowments common to all humans, so agreement among persons is possible. Thirdly, objectivity involves immunity to deep worldview differences or philosophical debates, thereby allowing a worldwide scientific community to exist and flourish. A major reason why science is respected is that it cuts across political, cultural, and religious divisions.

Realism, as regards the physical world, is the philosophical theory that both human thoughts and independent physical objects exist and that human endowments render the physical world substantially intelligible and reliably known. Scientific realism embodies the claim that the scientific method provides rational access to physical reality, generating much objective knowledge.

The full force of science's claims results from the joint assertion of all four: rationality, truth, objectivity, and realism. Science claims to have a rational method that provides humans with objective truth about physical reality.

Science is both similar to and different from common sense in various respects. The concepts of rationality, truth, objectivity, and realism are rich and meaningful precisely because they are not unique to science but rather are shared by common sense, philosophy, history, law, and so on. Also, science inherits indispensable presuppositions about the world being real and comprehensible from common sense. But scientific method is more exacting and unnatural than is common-sense thinking. Also, scientific findings are often surprising and even bizarre relative to common-sense beliefs.

Study questions

(1) Define rationality. In which academic disciplines besides science is rationality also applicable and important?
(2) Define truth. How would you compare and relate the correspondence, coherence, and pragmatic theories of truth?
(3) Define objectivity. What are the three interrelated aspects of objectivity and why is objectivity important in science?
(4) Define realism. What are the two basic tenets of realism, and what philosophical positions result from denying one or the other of those tenets?
(5) How would you relate science and common sense?

3

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?

4

Science's contested rationality

Does science have a rational method of inquiry that provides humans with a considerable amount of objective truth about physical reality? Certainly, a reply of "yes" represents the traditional claims of mainstream science, as delineated in Chapter 2. Furthermore, anyone who confidently believed the scientific story in Chapter 3 that water is H_2O has given every appearance of being in the camp that replies "yes" to this question.

Nevertheless, a controversy has raged over science's claims of rationality and truth, especially in the 1990s, although with roots going back to the 1960s and even back into antiquity. This controversy had such intensity in the 1990s that it went by the name of the "science wars" and even made the front pages of the world's leading newspapers.

Views that directly contradict and intentionally erode mainstream science are this chapter's topic. In this book that explicitly and repeatedly aligns with mainstream science, why devote a whole chapter to these contrary positions? Two reasons may be suggested.

First, for better or for worse, attacks on science's rationality have substantial cultural influence. The specific arguments and inflammatory rhetoric of "science wars" quickly came and went in a mere decade, which is quite ephemeral in the grand sweep of history, but skeptical and relativistic attacks on truth are perennial features of intellectual history. So, attacks on science's rationality are too influential and persistent to be ignored.

Second and more important, "those who know only their side of a case know very little of that" (Susan Haack, in Gross, Levitt, and Lewis 1996:57). What hinders scientists the most from mastering scientific method in order to enhance perspective and increase productivity is not their opponents' attacks but rather their own complacency – assuming that they already know scientific method well, and hence no further effort or study is required. Exposure to the other side attacking science can press the incisive questions that disturb insidious complacency and thereby prompt rigorous answers.

This chapter begins by considering who has legitimate rights to be auditors of science: scientists only, or else additional scholars also. It then examines four deadly threats to science's rationality: elusive truth, theory-laden data, incommensurable paradigms, and empty consensus. Reactions to these woes are reviewed, emphasizing articles in *Nature* and other scientific journals that are especially visible to scientists. The posture of the American Association for the Advancement of Science (AAAS) is also noted. Finally, a suggestion is offered for discerning the principal action in this complex debate, namely, whether an attack on rationality targets science alone, or else both science and common sense. This chapter introduces debates over science's rationality, leaving resolution to subsequent chapters, especially Chapter 14.

Science's auditors

Businesses have long been accustomed to having external auditors check their financial assets, liabilities, and ratings. But, increasingly, scientists have to get used to facing an accounting, although in their case the account is intellectual rather than financial. Many philosophers, historians, sociologists, and others have become external auditors of science. Their ratings of science's claims of rationality and truth are becoming increasingly influential, strongly affecting public perceptions of science.

This situation raises questions. Do philosophers and other nonscientists have a right to check science's claims? Or should scientists have the prerogative of setting their own standards for their truth claims without interference from anyone else?

Precisely because science is one of the liberal arts and because such fundamental intellectual notions as rationality and truth pervade the liberal arts, certainly it is within the purview of philosophy and history and other disciplines to have a voice in the weighing of science's intellectual claims. Every scientific claim of truth, expressed either as a certainty or as a probability, has both scientific and philosophical dimensions. Especially the general principles of scientific method, as contrasted with specialized techniques, have strong connections with many disciplines across the humanities.

Much, and perhaps most, of the probing of science's method and rationality by philosophers, historians, and sociologists is simply an earnest attempt to determine exactly what science's actual methods imply for science's legitimate claims. It would be decidedly unrealistic, however, not to recognize that some of this probing constitutes a militant call for scientists to promise less and for the public to expect less – much less! Scholars with relativistic, skeptical, and postmodern leanings routinely reach verdicts on science that are much more negative than what even the most cautious scientists reach.

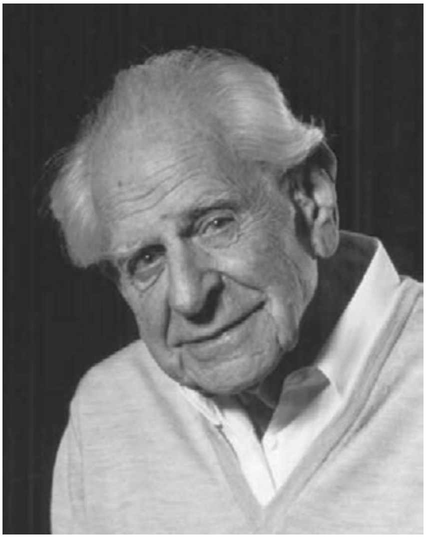

Figure 4.1 An important philosopher of science, Sir Karl Popper. (This photograph by David Levenson is reproduced with kind permission of Black Star.)

During the second half of the twentieth century, four philosophers of science have been especially prominent: Sir Karl Popper (1902–1994), Imre Lakatos (1922–1974), Thomas Kuhn (1922–1996), and Paul Feyerabend (1924–1994). They are the four irrationalists of Stove (1982) and the four villains of Theocharis and Psimopoulos (1987). Among philosophers, numerous philosophers of science are well known; but among scientists, Popper and Kuhn probably are better known than all the others combined.

The earliest of these four philosophers is Popper, shown in Figure 4.1. His reassessment of science's claims began with the publication of *Logik der Forschung* in 1934, which appeared in English as *The Logic of Scientific Discovery* in 1959 (second edition 1968). "Popper is far and away the most influential philosopher of modern science – among scientists if not other philosophers. He is best known for his assertion that scientific theories can never be proved through experimental tests but only disproved, or 'falsified'" (Horgan 1992). He had two particularly influential students, Imre Lakatos and Paul Feyerabend. An especially important contribution has been *The Structure of Scientific Revolutions* by Kuhn (1962, second edition 1970). It has sold more than a million copies in 20 languages and is commonly considered "the most influential treatise ever written on how science does (or does not) proceed" (Horgan 1991).

The incisive thinking and penetrating analyses of Popper, Kuhn, and other scholars have had many positive effects. Especially valuable are their effective criticisms of the logical empiricism that had preceded their generation, Popper's insistence on falsifiability, and Kuhn's recognition of the human and historical elements in science. Nevertheless, their writings have also mounted a sustained and influential attack on science's rationality, even though scientists often fail to recognize that. These critics have challenged science with four deadly woes: elusive truth, theory-laden data, incommensurable paradigms, and empty consensus.

Elusive truth

The first of the four deadly woes is elusive truth. What criterion can demarcate science from nonscience? In 1919, that question triggered Popper's interest in the philosophy of science (Popper 1974:33). He clearly distinguished that question, of whether or not a theory is scientific, from the different question of whether or not a theory is true. His question was occasioned by various claims that Einstein's physics, Marx's history, Freud's psychology, and Adler's psychology were all scientific theories, whereas Popper suspected that only the first of those claims was legitimate. Exactly what was the difference?

The received answer, from Francis Bacon several centuries earlier and from logical empiricists more recently, was that science is distinguished from pseudoscience and philosophy (especially metaphysics) by its empirical method, proceeding from observations and experiments to theories by means of inductive generalizations. But that answer did not satisfy Popper because admirers of Marx, Freud, and Adler also claimed an incessant stream of confirmatory observations to support their theories. Whatever happened was always and readily explained by their theories. What did that confirm? "No more than that a case could be interpreted in the light of the theory" (Popper 1974:35).

By sharp contrast, Einstein's theory of relativity could not sit easily with any and all outcomes. Rather, it made specific and bold predictions that put the theory at risk of disconfirmation if observations should turn out to be contrary to expectation. Einstein's theory claimed that gravity attracts light just as it attracts physical objects. Accordingly, starlight passing near the sun would be bent measurably, making a star's location appear to shift outward from the sun. Several years later, in 1919, a total eclipse of the sun afforded an opportunity to test that theory. An expedition led by Sir Arthur Eddington made the observations, clearly showing the apparent shift in stars' positions and thus confirming Einstein's theory. What impressed Popper most of all was the risk that relativity theory took, because an observation of no shift would have proved the theory false.

So, comparing supposedly "scientific" theories that are ready to explain anything with genuinely scientific theories that predict specific outcomes and thereby risk disconfirmation, Popper latched on to falsifiability as the essential criterion that demarcates science from nonscience. "Irrefutability is not a virtue of a theory (as people often think) but a vice.... [The] criterion of the scientific status of a theory is its falsifiability" (Popper 1974:36–37).

Notice that science was distinguished by falsification, not verification. Popper insisted that conjectures or theories could be proved false but no theory could ever be proved true. Why? Because he respected deductive logic but agreed with David Hume that inductive logic is a failure (Popper 1974:42). No quantity of observations can possibly allow induction to verify a general theory because further observations might bring surprises.

Hence, the best that science can do is to offer numerous conjectures, refute the worst with contrary data, and accept the survivors in a tentative manner. Conjecture followed by refutation was the scientific method, by Popper's account. But that implies that although "we search for truth ... we can never be sure we have found it" (Popper 1974:56). Truth is forever elusive. So, Popper offered his demarcation criterion of falsifiability to separate science from nonscience, but at the cost of separating science from truth.

Theory-laden data

The second of four deadly woes is theory-laden data. A prominent feature of the logical empiricism that dominated the philosophy of science preceding Popper and Kuhn was a sharp boundary between data and theory. According to that view, true and scientific statements were based on empirical observations and their deductive logical consequences – hence the name, logical empiricism. By contrast, Popper insisted that observations are deeply theory-laden: "But sense-data, untheoretical items of observation, simply do not exist.... We can never free observation from the theoretical elements of interpretation" (Karl Popper, in Lakatos and Musgrave 1968:163). Why? This claim that data are theory-laden has many facets, but here it must suffice to mention three principal arguments.

First, in order to make any observations at all, scientists must be driven by a theoretical framework that raises specific questions and generates specific interests. Popper (1974:46) explained the point nicely: "But in fact the belief that we can start with pure observations alone, without anything in the nature of a theory, is absurd.... I tried to bring home the same point to a group of physics students in Vienna by beginning a lecture with the following instructions: 'Take a pencil and paper; carefully observe, and write down what you have observed!' They asked, of course, *what* I wanted them to observe. Clearly the instruction, 'Observe!' is absurd.... Observation is always selective. It needs a chosen object, a definite task, an interest, a point of view, a problem."

Second, what may seem to be a simple observation statement, put to work to advance one hypothesis or to deny another, actually has meaning and force only within an involved context of theory. For example, a pH meter may give a reading of 6.42, but the interpretation of that datum depends on the validity of a host of chemical and electronic theories involved in the design and operation of that instrument.

Third, theory choice involves numerous criteria that entail subtle trade-offs and subjective judgments. For example, scientists want theories to fit the observational data accurately and also want theories to be simple or parsimonious. But if one theory fits the data more accurately whereas another theory is more parsimonious, which theory accords better with the data? Clearly, theory choice is guided not only by the observational data but also by some deep theories about scientific criteria and method.

This problem that data are theory-laden is related to a similar problem, the underdetermination of theory by data. For any given set of observations, it is always possible to construct many different and incompatible theories that will fit the data equally well. Consequently, no amount of data is ever adequate to determine that one theory is better than its numerous equal alternatives.

What do such problems mean for science? "But if observations are theory laden, this means that observations are simply theories, and then how can one theory falsify (never mind verify) another theory? Curiously, the full implications of this little complication were not fully grasped by Popper, but by Imre Lakatos: not only are scientific theories not verifiable, they are not falsifiable either" (Theocharis and Psimopoulos 1987).

So the first woe was that science could not verify truths. Now this second woe is that science cannot falsify errors either. Science cannot declare any theory either true or false! "So back to square one: if verifiability and falsifiability are not the criteria, then what makes a proposition scientific?" (Theocharis and Psimopoulos 1987). These are huge problems, and yet there follows a third woe.

Incommensurable paradigms

The third of four deadly woes is incommensurable paradigms. "Thomas S. Kuhn unleashed 'paradigm' on the world," reads the subtitle of an interview with him in *Scientific American* (Horgan 1991). It was reported that "Kuhn . . . traces his view of science to a single 'Eureka!' moment in 1947. . . . Searching for a simple case history that could illuminate the roots of Newtonian mechanics, Kuhn opened Aristotle's *Physics* and was astonished at how 'wrong' it was. How could someone so brilliant on other topics be so misguided in physics? Kuhn was pondering this mystery, staring out of the window of his dormitory room ('I can still see the vines and the shade two thirds of the way down'), when suddenly Aristotle 'made sense.' . . . Understood on its own terms, Aristotle's physics 'wasn't just bad Newton,' Kuhn says; it was just different. . . . He wrestled with the ideas awakened in him by Aristotle for 15 years. . . . 'I sweated blood and blood and blood,' he says, 'and finally I had a breakthrough.' The breakthrough was the concept of paradigm."

Just what is a paradigm? The meaning of Kuhn's key concept is disturbingly elusive. Margaret Masterman (in Lakatos and Musgrave 1970:59–89) counted 21 different meanings, and later in that book, Kuhn himself admitted that the concept was "badly confused" (p. 234). In response to criticisms, Kuhn clarified two main meanings: a paradigm is an exemplar of a past scientific success, or is the broad common ground and disciplinary matrix that unites particular groups of scientists at particular times.

The latter, broad sense is most relevant here. A paradigm is a "strong network of commitments – conceptual, theoretical, instrumental, and methodological" (Kuhn 1970:42). Scientific ideas do not have clear meanings and evidential support in isolation but rather within the broad matrix of a paradigm. For example: "The earth orbits around the sun" is meaningless apart from concepts of space and time, theories of motion and gravity, observations with the unaided eye and with various instruments, and a scientific methodology for comparing theories and weighing evidence.

The history of science, in Kuhn's view, has alternating episodes of normal science, which refine and apply an accepted paradigm, and episodes of revolutionary science, which switch to a new paradigm because anomalies proliferate and unsettle the old paradigm. A favorite example is Newton's mechanics giving way to Einstein's relativity when experiments of many kinds piled up facts that falsified the former but fit the latter theory.

But why did Kuhn speak of revolutions in science when others have been content to speak of progress? The problem is that different paradigms, before and after a paradigm shift, are incommensurable. This term means that no common measure or criterion can be applied to competing paradigms to make a rational, objective choice between them. "In learning a paradigm the scientist acquires theory, methods, and standards together, usually in an inextricable mixture. Therefore, when paradigms change, there are usually significant shifts in the criteria determining the legitimacy both of problems and of proposed solutions" (Kuhn 1970:109). Also, in a paradigm shift, the very meanings of key terms shift, so scientists are not talking about the same thing before and after the shift, even if some words are the same. For example, "Kuhn realized that Aristotle's view of such basic concepts as motion and matter were totally unlike Newton's" (Horgan 1991).

Well, if successive paradigms are incommensurable, what does that imply for science's rationality? In his interview in *Scientific American*, Kuhn remarked, "with no trace of a smile," that science is "arational" (Horgan 1991). To say that science is arational is to say that science is among those things, like cabbage, that have neither the property of being rational nor the property of being irrational. Consequently, saying that science is arational is an even stronger attack on science's rationality than saying that science is irrational.

What happens to realism? The interview by Horgan (1991) says that Kuhn's "most profound argument" is that "scientists can never fully understand the 'real world,'" with the real world sequestered here in scare quotes. "There is, I think, no theory independent way to reconstruct phrases like 'really there'; the notion of a match between the ontology of a theory and its 'real' counterpart in nature now seems to me illusive in principle" (Kuhn 1970:206). This detachment of science from nature is expressed with complete finality by these strong words, "illusive in principle."

What happens to truth? Science has no truth. Indeed, what should be said is "Not that scientists discover truth about nature, nor that they approach ever closer to the truth," because "we cannot recognize progress towards that goal" of truth (Thomas Kuhn, in Lakatos and Musgrave 1970:20). Likewise, the back cover of the current edition (1970) of Kuhn's book quotes, unashamedly and approvingly, the review in *Science* by Wade (1977) saying that "Kuhn does not permit truth to be a criterion of scientific theories."

Obviously scandalized, Theocharis and Psimopoulos (1987) observed that "according to Kuhn, the business of science is not about truth and reality; rather, it is about transient vogues – ephemeral and disposable paradigms. In fact three pages from the end of his book *The Structure of Scientific Revolutions*, Kuhn himself drew attention to the fact that up to that point he had not once used the term 'truth'. And when he used it, it was to dismiss it: 'We may have to relinquish the notion that changes of paradigm carry scientists . . . closer and closer to the truth.'" With rationality, realism, and truth gone, there follows yet another woe for science.

Empty consensus

The fourth and final deadly woe is empty consensus. For more than two millennia since Aristotle, and preeminently in the fledgling universities in Oxford and Paris during the 1200s, philosopher-scientists labored to develop, refine, and establish scientific method. The intention was for scientific method to embody and support science's four traditional claims of rationality, truth, objectivity, and realism. But various arguments developed during the past century, including the problems discussed in the preceding three sections, have led some scholars to abandon science's traditional claims and substitute mere consensus among scientists.

"According to the common-sense view, of course, the assent of the [scientific] community is dictated by certain agreed standards, enabling us to say that the preferred theory is the better one. But Kuhn turns this upside down. It is not a higher standard which determines the community's assent, but the community's assent which dictates what is to count as the highest standard" (Banner 1990:12). What makes a statement scientific is that scientists say it; nothing more. Sociology replaces method in that account of what is scientific.

A particularly radical reinterpretation of science came from Paul Feyerabend. In an interview with Feyerabend in *Science*, "Equal weight, he says, should be given to competing avenues of knowledge such as astrology, acupuncture, and witchcraft. . . . 'Respect for all traditions,' he writes, 'will gradually erode the narrow and self-serving "rationalism" of those [scientists] who are now using tax money to destroy the traditions of the taxpayers, to ruin their minds, to rape their environment, and quite generally to turn living human beings into well-trained slaves.' . . . Feyerabend is dead set against what has been called 'scientism' – the faith in the existence of a unique [scientific] 'method' whose application leads to exclusive 'truths' about the world" (Broad 1979).

Similarly, a more recent interview with Feyerabend in *Scientific American* says that "For decades, . . . Feyerabend . . . has waged war against what he calls 'the tyranny of truth.' . . . According to Feyerabend, there are no objective standards by which to establish truth. 'Anything goes,' he says. . . . 'Leading intellectuals with their zeal for objectivity . . . are criminals, not the liberators of mankind.' . . . Jutting out his chin, he intones mockingly, 'I am searching for the truth. Oh boy, what a great person.' . . . Feyerabend contends that the very notion of 'this one-day fly, a human being, this little bit of nothing' discovering the secret of existence is 'crazy.' . . . The unknowability of reality is one theme of . . . Feyerabend" (Horgan 1993).

Ironically, these four woes bring the status of science full circle. Popper started with the problem of demarcating science from nonscience in order to grant credibility to science and to withhold credibility from nonscience. Despite considerable limitations, science was something special. But a mere generation later, his student Feyerabend followed his teacher's ideas to their logical conclusion by judging that science is neither different from nor superior to any other way of knowing. Science started out superior to astrology; it ended equivalent. For millennia, science involved methodology for finding objective truth; it ended with sociology for explaining empty consensus.

Finally, so what? After having told us that science is arational, that science finds no truth, that reality is eternally illusive in principle, and that science's supposed claims are to be explained away in sociological terms, a calm Kuhn tells us that "I no longer feel that anything is lost, least of all the ability to explain scientific progress, by taking this position" (Thomas Kuhn, in Lakatos and Musgrave 1970:26). For Kuhn, the rationality, truth, objectivity, and realism that scientists are accustomed to, just do not matter.

Reactions from scientists

The preceding four sections discussed four deadly woes: elusive truth, theory-laden data, incommensurable paradigms, and empty consensus. How do scientists react? Do they think that these philosophical criticisms are valid, forcing honest scientists to adjust and downgrade their claims, or not?

The following account of scientists' reactions focuses on material that is readily seen by scientists, especially articles in *Nature* and *Science*. The first notable exchange began with the provocative commentary by Theocharis and Psimopoulos (1987) in *Nature*. It stimulated a lively correspondence, from which *Nature* published 18 letters, until the editor closed the correspondence and gave the authors an opportunity to reply (*Nature* 1987, 330:308, 689–690; 1988, 331:129–130, 204, 384, 558; reply 1988, 333:389).

The dominant tenor of the 18 letters to the editor was that of numerous scientists rushing in to defend Popper and Kuhn from what they perceived as an unreasonable or even malicious attack by Theocharis and Psimopoulos. One letter even recommended that Theocharis and Psimopoulos (and perhaps also the journal *Nature*) offer Sir Karl Popper a public apology. Some letters rejected the claim that objective truth was important for science. One letter claimed that the "most basic truth is that there can be no objective truth." Another reader replaced truth with prediction: "This process of making ever better prediction *is* scientific progress, and it circumvents entirely the problem of defining scientific truth."

One of the strongest letters was from sociologist Harry Collins. Apparently considering himself to have ascended to high moral ground indeed, he suggested that "The only thing that makes clear good sense in Theocharis and Psimopoulos is the claim that the privileged image of science has been diminished by the philosophical, historical and sociological work of past decades. One hopes this is the case. Grasping for special privilege above and beyond the world we make for ourselves – the new fundamentalism that Theocharis and Psimopoulos press upon us – indicates bankruptcy of spirit luckily not yet widespread in the scientific community." So pursuit of truth had been transmuted into bankruptcy of spirit!

Some other reactions, however, were favorable. One responder wrote sympathetically that "Philosophical complacency . . . will not do; contrary to what both sceptics and conservatives often seem to believe, philosophical questions do matter." Another responded that "There are very good reasons why twentieth century philosophy of science, under the malign influence of Popper through to Feyerabend, is profoundly hostile to science itself. . . . It is indeed unfortunate that many scientists, through ignorance, quote these philosophers approvingly. The most effective victories are those in which the losers unwittingly assist their opponents."

In their reply to these 18 letters, Theocharis and Psimopoulos offered a poignant and intriguing remark about the uniqueness of the contemporary scene: "Natural philosophy has had enemies throughout its 2,600 or so years of recorded history. But the present era is unique in that it is the first civilized society in which an effective antiscience movement flourishes contemporaneously with the unprecedently magnificent technological and medical applications of modern science. This is a curious paradox which cries out for clarification."

Another interesting exchange was precipitated by the publication of a book by Collins and Pinch (1993). It was reviewed and criticized by N. David Mermin in

Physics Today [1996, 49(3):11, 13; 49(4):11, 13], with further exchanges [1996, 49(7):11, 13, 15; 1997, 50(1):11, 13, 15, 92, 94–95]. Mermin strongly rejected Collins and Pinch's conclusion that "Science works the way it does not because of any absolute constraint from Nature, but because we make our science the way that we do." The collective import of many such declarations was that science does not discover objective truths about physical reality but rather just constructs consensus among scientists. Obviously, Mermin said, scientists are humans involved in a social structure that is a real and integral aspect of our science, but "Agreement is reached not just because scientists are so very good at agreeing to agree." Mermin suggested that a crucial feature of science that Collins and Pinch overlooked in their denigrating account was the role of interlocking evidence: "an enormous multiplicity of strands of evidence, many of them weak and ambiguous, can make a coherent logical bond whose strength is enormous."

The letters to the editor were generally sympathetic to Mermin's defense of science's rationality. One letter offered the perceptive remark that "No modern-day consensus on the nature of science will be reached until we agree that what we are talking about is neither sociology nor science, but philosophy." Another letter declared quite simply that "There really are results and facts."

Another important exchange began with a commentary on science wars in *Nature* by Gottfried and Wilson (1997). Subsequently, Colin Macilwain and David Dickerson continued the discussion in *Nature* (1997, 387:331–334); readers provided four letters, and Gottfried and Wilson replied (1997, 387:543–546), and then two more letters appeared (1997, 388:13; 389:538).

The main concern in Gottfried and Wilson's 1997 commentary was with attacks on science from sociologists, in contrast to Theocharis and Psimopoulos's 1987 commentary in the same journal a decade earlier that had focused on attacks from philosophers. A school of sociology, so-called Science Studies, had vigorously attacked science's traditional claims. Variants of that movement went under several names, such as the "strong program" or the Edinburgh school of sociology, but here the brief name "constructivism" suffices. Gottfried and Wilson got quickly to the very heart of the debate over science's status: "Scientists eventually settle on one theory on the basis of imperfect data, whereas logicians have shown that a finite body of data cannot uniquely determine a single theory. Among scientists this rarely causes insomnia, but it has tormented many a philosopher."

Seven lines of evidence were cited to show that science has a strong grip on reality: (1) steadily improving predictions, often unambiguous, precise, diverse, and even surprising; (2) increasingly accurate and extensive data; (3) increasingly specific and comprehensive theories; (4) interlocking evidence of diverse sorts; (5) progress over time in describing and explaining nature; (6) reproducible experiments; and (7) science-based technology that works. Of those seven witnesses to science's success, the first, "predictive power," was "the strongest evidence that the natural sciences have an objective grip on reality."

A particularly notorious episode in the science wars, mentioned by Gottfried and Wilson (1997), was the so-called Sokal affair. To spoof postmodern and constructivist views of science, Sokal (1996) published an article in *Social Text*, only later to expose it as a hoax (Alan Sokal, in Koertge 1998:9–22; Sokal 2008). "'It took me a lot of writing and rewriting and rewriting before the article reached the desired level of unclarity,' he chuckles," in an interesting interview in *Scientific American* (Mukerjee 1998). That hoax provoked front-page articles in the *New York Times*, the *International Herald Tribune*, the London *Observer*, and *Le Monde*.

A recent essay in *Nature* by sociologist Collins (2009) had the byline, "Scientists have been too dogmatic about scientific truth and sociologists have fostered too much scepticism – social scientists must now elect to put science back at the core of society." This two-page essay provides an ideal summary for Collins's work over the preceding couple of decades. He characterized the sociology of science (or "science studies") as having three waves. The first wave "coincided with post-war confidence in science" after the Second World War, during which "social scientists took science to be the ultimate form of knowledge." The second wave began in the 1960s and culminated in the science wars that earnestly began around 1990 and essentially ended around 2000, and it "was characterized by scepticism about science." Collins (2009) proposed a new third wave "to counter the scepticism that threatens to swamp us all" and "to put the values that underpin scientific thinking back in the centre of our world." His main suggestion for implementing this third wave was "to analyse and classify the nature of expertise to provide the tools for an initial weighting of opinion," as explained more fully in a book that he and his colleagues had recently authored. He also suggested that "scientists must think of themselves as moral leaders" promoting "the good society."

His critique of this renounced skepticism had the crucial insight – which every science student and professional should fully appreciate and which Collins expressed skillfully and concisely – that skepticism is utterly and irremediably unfalsifiable. "By definition, the logic of a sceptical argument defeats any amount of evidence" because the skeptic can always appeal to several potential philosophical problems that cut deeper than any empirical evidence, such as that "one cannot be sure that the future will be like the past." And the troubling consequence rapidly follows that "One can justify anything with scepticism" since it recognizes no real knowledge to constrain belief or guide action.

Nevertheless, this essay's renunciation of skepticism about science left intact the chief tenet of this skepticism, namely, that science finds no settled truth. Scientists are "reaching towards universal truths but inevitably falling short" and they "must teach fallibility, not absolute truth." Again, "Science's findings . . . are not certain. They are a better grounding for society precisely, and only, because they are provisional.” Consequently, “when we outsiders judge scientists, we must do it not to the standard of truth, but to the much softer standard of expertise.”

However, one need not search very far to see that this insistent and repeated rejection of truth claims, which has been a persistent theme in Collins’s publications for two decades, is wholly uncharacteristic of actual science. For instance, turn the pages of the 2009 issue of *Nature* containing Collins’s essay to glance at its other articles. They concern the molecular basis of transport and regulation in the Na^+/betaine symporter BetP, a candidate sub-parsec supermassive binary black hole system, the electronic acceleration of atomic motions and disordering in bismuth, the innate immune recognition of infected apoptotic cells directing T_H17 cell differentiation, transcriptome sequencing for detecting gene fusions in cancer, determining protein structure in living cells by in-cell NMR spectroscopy, and such. The rest of this issue of *Nature* is immersed and soaked in truth claims, of which some are probable to a specified degree and some are certain, based on extensive evidence and careful reasoning that has been checked by competent colleagues and peer reviewers. Doubtless, someone somewhere is exaggerating science’s role, but such nonsense is not characteristic of the mainstream science that readers encounter in the pages of *Nature* and *Science*, and neither is such nonsense best refuted by the opposite exaggerating of science’s complete inability to find any settled truth.

Collins’s essay prompted four replies. The title of the first reply effectively captured the tenor of this correspondence: “Let’s not reignite an unproductive controversy.” In my view, Collins’s essay denounces exaggerated claims of science’s powers, only to substitute exaggerated claims of science’s limits, exaggerated fears of skepticism’s threat to swamp us all, exaggerated pronouncements (in a science journal!) on religion’s demerits, exaggerated expectations for science’s role in politics and society, and exaggerated plaudits for scientific expertise after detaching expertise from truth.

Popper and Kuhn appear not only in contests over science’s rationality but also when scientists publish routine research papers citing them. Such citations are moderately common, with Popper’s *The Logic of Scientific Discovery* having more than 12,000 citations and Kuhn’s *The Structure of Scientific Revolutions* having more than 44,000 citations. Most scientists have at least a passing familiarity with those influential intellectuals. What concepts are scientists drawing from such philosophers in routine scientific publications?

For the most part, despite occasional noteworthy exceptions, it must be said that the routine use of Popper and Kuhn’s ideas by scientists is rather selective and superficial. For instance, the first of the 18 replies to Theocharis and Psimopoulos (1987), written by a physiologist who also taught a course in the philosophy of science, was quite revealing. “Popper began it all by his concern to distinguish good science from bad. He identified Einstein as good and Adler as bad by characterizing Einstein’s predictions as *falsifiable* but not as false. . . . I share the view that the next stage of Popper's thought sees him following up certain ideas to unbalanced and therefore somewhat antirational conclusions, but this first, key perception [regarding falsifiability] is firmly on the side of objectivity and truth. This is the one bit of Popper that I teach." His sensible posture toward the philosophers was that "If their accounts are unbalanced, it is up to us [scientists] to balance, not dismiss them."

The one bit of Popper that does show up frequently in scientists' research papers is that a proposed hypothesis must make testable predictions that render the hypothesis falsifiable. And, more pointedly, a scientist should give his or her own favored hypothesis a trial by fire, deliberately looking for potentially disconfirming instances, not just instances that are likely to be confirming. Doubtless, this is wholesome advice. But is this some fancy, new insight? Hardly! It is as old as ancient *modus tollens* arguments (not *B*; *A* implies *B*; therefore not *A*) and the medieval Method of Falsification of Robert Grosseteste. Looking for potentially contradictory evidence seems more in the province of simple honesty than fancy philosophy.

Similarly, the one bit of Kuhn that does show up frequently in scientists' writings is the dramatic idea of a paradigm shift. Needless to say, this idea is particularly popular among those scientists who take themselves to be the innovators who are precipitating some big paradigm shifts in their own disciplines. Of course, the standard claim in scientists' papers is that their shiny new paradigms are a whole lot better than their predecessors, and even are true or at least approximately true. But unwittingly such scientists are bad disciples of their presumed master, Kuhn. His own view was that successive paradigms are incommensurable, so it makes no sense whatsoever to say that one paradigm is better than another. Of course, Kuhn's own view takes all the fun and prestige out of coming up with a slick new paradigm! So it is not too surprising that scientists have generally failed to get that discouraging bit of Kuhn.

What is the bottom line? The bad news is a recent history of scientists mostly citing skeptical philosophers of science whose actual views undermine science's traditional claims but evading potential harm by selective and superficial use of the occasional bits that are sensible for science practitioners. The good news is that nothing is keeping scientists from a future history of using many bits of great ideas from mainstream philosophers of science for the practical purposes of increasing productivity and enhancing perspective.

The AAAS posture

For several decades, particularly since the books by Popper and Kuhn appeared in 1959 and 1962, science's traditional claims of rational realism and objective truth have been under significant reappraisal and even sustained attack. Does the AAAS rebut these new ideas about science, accept them, or just ignore them?

Their most general statements about science reveal most incisively just what the AAAS takes science to be. For instance, "science is the art of interrogating nature" (AAAS 1990:17). That simple but profound remark claims that science is objective in the fundamental sense of being about an object with its own independent existence and properties. Also, truth is sought: "When faced with a claim that something is true, scientists respond by asking what evidence supports it" (AAAS 1989:28). The basic elements in scientific method are observation and evidence, controlled experiments, and logical thought (AAAS 1989:25–28). Such remarks presume and express science's traditional claims of rationality, truth, objectivity, and realism.

The AAAS also expresses some ideas associated with Popper and Kuhn. For instance, scientific thinking demands falsifiability, as Popper insisted. "A hypothesis that cannot in principle be put to the test of evidence may be interesting, but it is not scientifically useful" (AAAS 1989:27; also see AAAS 1990:xiii). And data are theory-laden because theory guides the choice, organization, and interpretation of the data (AAAS 1989:27, 1990:17–18). Likewise, scientific research is guided by paradigms that are "metaphorical or analogical abstractions" that "dictate research questions and methodology," as Kuhn emphasized (AAAS 1990:21, 24). "Because paradigms or theories are products of the human mind, they are constrained by attitudes, beliefs, and historical conditions" (AAAS 1990:21).

Science has a decidedly human face, quite unlike its earlier images offered by Francis Bacon in the 1600s or the logical empiricists in the early 1900s. Indeed, "human aspects of inquiry . . . are involved in every step of the scientific process from the initial questioning of nature through final interpretation" (AAAS 1990:18). "Science as an enterprise has individual, social, and institutional dimensions" (AAAS 1989:28). This humanity brings risks and biases: "Scientists' nationality, sex, ethnic origin, age, political convictions, and so on may incline them to look for or emphasize one or another kind of evidence or interpretation" (AAAS 1989:28). But, on balance, scientists do attempt to identify and reduce biases: "One safeguard against undetected bias in an area of study is to have many different investigators or groups of investigators working in it" (AAAS 1989:28).

How much success does science enjoy in getting at the truth? "Scientific knowledge is not absolute; rather, it is tentative, approximate, and subject to revision" (AAAS 1990:20), and "scientists reject the notion of attaining absolute truth and accept some uncertainty as part of nature" (AAAS 1989:26). "Current theories are taken to be 'true,' the way the world is believed to be, according to the scientific thinking of the day" (AAAS 1990:21). Note that "true," here sequestered in scare quotes, is equated to nothing more real or enduring than "the scientific thinking of the day." Furthermore, science's checkered history "underscores the tentativeness of scientific knowledge" (AAAS 1990:24).

Nevertheless, "most scientific knowledge is durable," and "even if there is no way to secure complete and absolute truth, increasingly accurate approximations can be made" (AAAS 1989:26). However, deeming durability to be something good or admirable presumes that durability is serving as some sort of truth surrogate, because otherwise the durability or persistence of a false idea is bad. Hence, switching from "true" to "durable" is not a successful escape from the issue of truth. One of the most positive remarks is that "the growing ability of scientists to make accurate predictions about natural phenomena provides convincing evidence that we really are gaining in our understanding of how the world works" (AAAS 1989:26).

All in all, the AAAS verdict is a nuanced mix of positives and negatives: "Continuity and stability are as characteristic of science as change is, and confidence is as prevalent as tentativeness. . . . Moreover, although there may be at any one time a broad consensus on the bulk of scientific knowledge, the agreement does not extend to all scientific issues, let alone to all science related social issues" (AAAS 1989:26, 30).

One must also observe, however, that the pages of AAAS (1989) catalogue literally hundreds of facts about the universe, the earth, cells, germs, heredity, human reproduction and health, culture and society, agriculture, manufacturing, communications, and other matters. Unquestionably, the vast majority of these facts are presented with every appearance of truth and certainty and without even a trace of revisability or tentativeness. For instance, science has declared that the earth moves around the sun (and around our galaxy), and the former theory that the earth is the unmoving center of the universe is not expected to make a stunning comeback because of some new data or theory!

Admittedly, it is awkward that some AAAS declarations sound as though they reflect the concept that all scientific knowledge is tentative, whereas other statements apparently present numerous settled certainties. Perhaps the AAAS verdict on science and truth is rather unclear, or perhaps some isolated statements lend themselves to an unbalanced or unfair reading relative to the overall message. Anyway, it may be suggested that, given a charitable reading, the AAAS position papers say that some scientific knowledge is true and certain, some is probable, and some is tentative or even speculative and that scientists usually have good reasons that support legitimate consensus about which level of certainty is justified for a given knowledge claim.

Although the AAAS acknowledges revolutionary changes in paradigms, they explicitly deny that successive paradigms are incommensurable or fail to move closer to the truth: "Albert Einstein's theories of relativity—revolutionary in their own right—did not overthrow the world of Newton, but modified some of its most fundamental concepts" (AAAS 1989:113; also see p. 26). Newton's mechanics and Einstein's relativity lead to different predictions about motions that can be observed, so they are commensurable; and relativity's predictions have been more accurate, so it is the better theory (AAAS 1989:114). And yet, looking to the future, physicists pursue "a more [nearly] complete theory still, one that will link general relativity to the quantum theory of atomic behavior" (AAAS 1989:114).

Likewise, the AAAS repeatedly discusses the logic of falsifiability. But, unlike Popper, they also repeatedly discuss the logic of confirmation, including sophisticated remarks about the criteria for theory choice (AAAS 1989:27–28, 113–115, 135). Also, the acknowledgement of science's human face causes no despair about humans rationally investigating an objective reality with considerable success.

With admirable candor, the AAAS (1990:26) recognizes that even their careful position papers "are set in a historical context and that all the issues addressed will and should continue to be debated." One curious feature of AAAS (1989, 1990) is that despite the numerous unmistakable allusions to Popper and Kuhn's influential ideas, those figures are neither named nor cited. In the future, it will be interesting to see whether the AAAS decides to engage science's external auditors more directly.

Clear targets

When scientists encounter philosophers and others in grand discussions of science's rationality, just one simple question is surpassingly most essential. What are the targets of an argument against rationality: science only, or else both science and common sense? These two options are depicted in Figure 4.2.

The attacks on science's rationality involve a thousand complicated technicalities, but the principal action concerns this one simple matter of the scope of an attack. If the target is science only, then the argument presents a challenge that scientists really need to answer. But, if the targets are science and common sense, then the argument is merely some variant of radical skepticism, and the scientific community is under no obligation to find it of any interest. Science *begins* with the presupposition that the physical world is comprehensible to us (AAAS 1989:25, 1990:16). Therefore, a legitimate attack on science's rationality must target science alone, not both science and common sense. Why this is so can be illuminated by an analogy.

People often have the perception that many disease organisms are difficult to kill because numerous terrible diseases still ravage millions of suffering persons, and scientists have no satisfactory cure. But, in fact, all of these viruses, bacteria, and other microbes are easy to kill – every last one of them. A strong dose of arsenic or cyanide could kill them all, not to mention the even easier expedient of merely heating them to 500°C. It is easy to kill any pathogen. The trick is not to kill the host at the same time! Medicine's challenge is to kill the pathogen *and* not kill the host. So a strong dose of arsenic fails to qualify as a medicine, not because it kills too little, but because it kills too much.

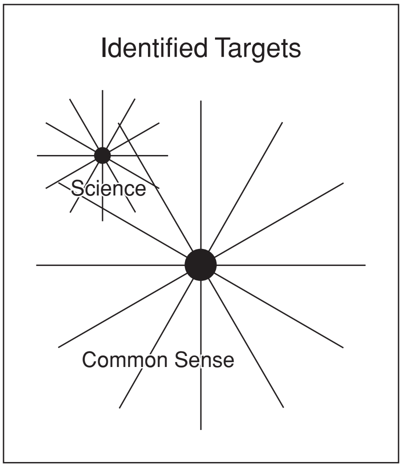

Figure 4.2 Identified targets for arguments against science's rationality. Arguments vary in their explosive force and intended targets. Some attack science only, whereas others attack both science and common sense. Because these two options call for very different analyses and responses, the targets of a given argument must be clearly identified.

Now, the same situation applies to science and common sense. Countless philosophical arguments and intellectual blunders kill common sense, which obviously kills science also. It is easy to kill both common sense and science. Indeed, a lackluster high school student can easily learn five skeptical objections in as many minutes – maybe our sense perceptions are unreliable, maybe some demon is deceiving us, maybe the physical world is only an illusion, maybe the future will be unlike the past, and so on. But, for any discipline such as science that begins with a nonnegotiable conviction that common sense delivers much truth because the world is comprehensible, a philosophical argument that kills science and common sense is unimpressive because it kills too much.

Consequently, the first and greatest burden placed on scientists when they read antiscientific arguments is to ask this discerning question: Does this philosophical argument kill science alone, or does it kill both science and common sense? Any argument that, if understood clearly and applied consistently, would imply that we cannot really know trifling trinkets of common-sense knowledge is just plain ridiculous, whether or not the scientist has enough philosophical training and acumen to spot and refute the specific steps at which the argument goes awry.

For example, Popper insisted that "We *cannot* justify our knowledge of the external world; *all* our knowledge, even our observational knowledge, is theoretical, corrigible, and fallible" (Karl Popper, in Lakatos and Musgrave 1968:164). Hence, in Popper's own estimation, problems extend to "*all* our knowledge" of any kind, including both science and common sense. Accordingly, this attack is suspect because it unsettles too much.

The defense of science's rationality begins with this insistence on clear targets for arguments against rationality. But this defense matures with painstaking, methodical development of the components of scientific thinking: presuppositions, evidence, and logic. That ensues in the following Chapters 5 to 11, after which my response to the four woes is given in the first section of the final Chapter 14.

Summary

Opinions about science's rationality and objective truth have always been strongly influenced by the claims of scientists themselves. But the assessments and judgments of philosophers, historians, sociologists, and others are becoming increasingly influential. External auditors are legitimate and beneficial because science is a liberal art and there is a rich traffic of fruitful ideas among the sciences and the humanities. Even highly critical views can be helpful, disturbing complacency and prompting scientists to think things through carefully.

Science's four traditional claims are rationality, truth, objectivity, and realism. But those claims have been under heavy attack, especially in terms of four intellectual problems: (1) Karl Popper claimed that empirical data could falsify a theory but never prove it, so science could never find truth. (2) Popper and others claimed that observations are theory-laden and that data underdetermined theory choice. From that, Imre Lakatos drew the implication that scientific theories cannot be falsified either, so science cannot declare any theory either true or false. (3) Thomas Kuhn said that paradigms are incommensurable, so science is arational. (4) Kuhn also said that what makes a statement scientific is merely that scientists say it. Accordingly, Paul Feyerabend concluded that there is nothing special about science.

The first notable exchange among scientists, philosophers, and others regarding science's rationality began with the commentary by Theocharis and Psimopoulos (1987) in *Nature*. Those scientists felt that the critiques by Popper and Kuhn and other philosophers were unjustified and exaggerated, but nevertheless quite influential, so it was incumbent upon the scientific community to give a satisfying defense of science's rationality, objectivity, and truth. More recent exchanges were prompted by a commentary by Gottfried and Wilson (1997) and an essay by Collins (2009) in *Nature*. Position papers from the AAAS have provided a mainstream institutional perspective.

Identifying the target of an argument against science's rationality is essential. An argument that attacks both science and common sense is simply some variant of radical skepticism, so the scientific community is not obliged to respond.

However, a full explanation and defense of science's rationality necessarily takes the form of an account of the presuppositions, evidence, and logic that together undergird science's rationality.

Study questions

(1) Have you encountered attacks on science's rationality? If so, are they coming from scientists or from others? How prevalent or influential do you perceive these attacks to be?
(2) In your own estimation, who are the legitimate auditors of science's claims?
(3) Recall the four deadly woes: elusive truth, theory-laden data, incommensurable paradigms, and empty consensus. Which one do you consider to be the most serious threat and why? How would you answer that threat in order to preserve science's rationality?
(4) Consider the reactions from scientists to the so-called science wars. Which two or three of the scientists' arguments do you think are the strongest? Can you think of any additional strong arguments that were not already mentioned in this chapter?
(5) Doubtless, the complexity of the four deadly woes means that any adequate response must take the form of a collection of numerous arguments. But such a collection needs to start somewhere. What do you regard as the first and most important clarification or argument?

5

Science's presuppositions

Essentially, a presupposition is a belief that is required to reach a particular conclusion, and yet it cannot possibly be proved. A presupposition cannot be proved in the ordinary sense of marshaling definitive evidence because presuppositions precede and empower evidence. But that does not necessarily mean that presuppositions are arbitrary and shaky. Rather, presuppositions should be chosen carefully, disclosed, and then legitimated. Because presuppositions are just as necessary as evidence for science to reach any conclusions, a reflective account of science must discuss them.

Although presuppositions and evidence are equally essential, in ordinary scientific discourse, the presuppositions are ignored, whereas the evidence is marshaled. Why? Within the context of ordinary science, the presuppositions needed in science are sensible and unproblematic and are taken for granted. Nevertheless, "Our presuppositions are always with us, never more so than when we think we are doing without them" (O'Hear 1989:54). Again, "Most scientists take for granted their metaphysical assumptions, but they are none the less necessary logically to the conclusions of science" (Caldin 1949:176).

This chapter's topic of presuppositions bears primarily on this book's purpose of enhancing perspective. To the extent that defending science's rationality is important for science's long-term health, however, this chapter is crucial. Primarily science's presuppositions, rather than its evidence or logic, prompt positive or negative assessments of science's rationality.

This chapter argues that science requires more logic, more evidence, more instrumentation, more education, and more work than does common sense, but nothing more by way of presuppositions. Presuppositions cannot be proved by logic or established by evidence; rather, they can be disclosed by philosophy and accepted by faith.

Historical perspective on presuppositions

Because presuppositions are the most subtle components of scientific method, some historical perspective is invaluable. Especially for scientists who have given science's presuppositions little thought, a brief historical survey provides a window into the various options and their implications.

Albertus Magnus (*c.* 1200–1280) handled science's presuppositions by an appeal to conditional necessity, a concept that ranks among the most important notions in the philosophy of science. He was building on the concept of suppositional reasoning that had been explained by Aristotle (384–332 BC). Albertus rendered the opening sentence of Book 2 of Chapter 9 of Aristotle's *Physics* as follows, with Aristotle's text in italic type and Albertus's amplification in roman type.

> "We ask therefore first *whether the necessity of physical things is a necessity simply or is a necessity 'ex suppositione'* and on the condition of some end that is presupposed. For example, a simple necessity is such that it is necessary that the heavy go down and the light go up, for it is not necessary that anything be presupposed for this for it to be necessary. Necessity 'ex conditione,' however, is that for whose necessity it is necessary to presuppose something, nor is it in itself necessary except 'ex suppositione'; and so it is necessary for you to sit if I see you sitting." (William A.Wallace, in Weisheipl 1980:116)

In Albertus's view, biology *could* be as certain as geometry: "Surely Albert entertained no doubts that . . . one could have certain and apodictic demonstrations even when treating of animals, provided the proper norms of *ex suppositione* reasoning were observed" (William A. Wallace, in Weisheipl 1980:127–128). For example, that (normal adult) horses eat grass and that Euclidean triangles have interior angles totaling 180 degrees have equal degrees of certainty, even though they have different grounds of certainty.

Suppositional reasoning became a device for demarcating a human-sized and public science apart from philosophical differences and theological debates. Bear in mind that in referring to philosophy, Albertus included natural philosophy or what we would now most commonly call science. Albertus "proposed to distinguish between philosophy and theology on methodological grounds, and to find out what philosophy alone, without any help from theology, could demonstrate about reality. . . . He acknowledged (with every other medieval thinker) that God is ultimately the cause of everything, but he argued that God customarily works through natural causes and that the natural philosopher's obligation was to take the latter to their limit" (Lindberg 2007:240–241).

In the subsequent formulations of Thomas Aquinas (*c.* 1225–1274), John Duns Scotus (*c.* 1265–1308), Jean Buridan (*c.* 1295–1358), and others, that notion of conditional necessity was gradually shifted in two significant ways. First, Aristotle and Albertus emphasized purpose in nature, but later views of scientific explanation gave this diminishing attention. Second, concern with necessity gave way to interest in certainty. Often, the motive for demonstrating that something is necessary had been to establish that it is certain. But necessity is a much richer concept than certainty, implicating a much larger and potentially more controversial story about how the world works.

Sir Francis Bacon (1561–1626) was an influential proponent of science. His *Novum Organum* claimed to offer a better scientific method than had his predecessors, especially Aristotle. It emphasized empirical evidence untainted by presuppositions. Bacon charged that someone led captive by presuppositions would reach a conclusion before doing proper experiments. Doubtless, Bacon's view of science, supposedly based on presuppositionless evidence, still typifies the way many scientists think about science.

David Hume (1711–1776) was a great skeptic. He thought that science's ambitions must be limited to describing our perceptions, avoiding philosophical speculations about some external physical world. But, despite his philosophical convictions, Hume conceded that common sense must rule in life's ordinary dealings. His writings reflect an awkward tension between common sense and philosophy that never gets resolved. Another challenging view was that of George Berkeley (1685–1753), who believed that only minds and ideas exist, and not physical objects.

Thomas Reid (1710–1796) was the great protagonist of common sense as the only secure foundation for philosophy and science, in marked contrast to Hume. Of course, previous ancient and medieval thinkers had developed the scientific method within a common-sensical framework. But subsequent challenges, especially from Berkeley and Hume, had necessitated exposing science's common-sense roots with greater clarity and force. According to Reid,

> Hume's error was to suppose that it made sense to justify first principles of our faculties by appeal to [philosophical] reason. It does not. . . . To attempt to justify the first principles of our faculties by reasoning is to attempt to justify what is the most evident by appeal to less evident premises, those of philosophers. . . . Philosophy, properly understood, does not justify these principles of common sense but grows from them as a tree grows from its roots. . . . The attempt to justify a conclusion that is evident to begin with, such as that I see a cat, by appeal to premises that are philosophically controversial is doomed to absurdity. When the conclusion of an argument is more evident to begin with than it could be shown to be by a philosophical argument, the latter is useless as the justification of the conclusion. . . . No such [philosophical] argument has the evidential potency of innate [common-sense] principles of the mind. (Lehrer 1989:19, 294)

Reid's conception of science based on common sense had five main elements.

(1) The Symmetry Thesis. An influential eighteenth-century science of the human mind, originating from John Locke (1632–1704), Berkeley, and Hume, said that real knowledge could be achieved only for our sensations and relations among sensations, not for objects supposedly causing our sensations, so science must settle for appearances rather than realities. As a corrective, Reid adopted a symmetry thesis that gave the internal world of sensations and external world of objects equal priority and status, with both taken as starting points for philosophical reflection.

(2) **Harmonious Faculties.** Hume and other skeptics granted philosophical reasoning priority over scientific observation. But Reid endorsed the basic reliability of all of our faculties, both sensory and mental, saying that "He must be either a fool or want to make a fool of me, that would reason me out of my reason and senses" (Hamilton 1872:104). Indeed, "Scepticism about the soundness of the sceptic's arguments is at least as justified as the scepticism which he urges upon us" (Dennis C. Holt, in Dalgarno and Matthews 1989:149).

(3) **Parity among Presuppositions.** Reid claimed a parity between realist and skeptical presuppositions. Reid noted that we have two choices: to trust our faculties as common sense enjoins, or not to trust our faculties and become skeptics. A critic may complain that Reid's appeal to common sense is dogmatic or circular: "Because propositions of common sense are foundational, it is not possible to provide constructive, independent grounds for their acceptance. The propositions of common sense constitute the final court of appeal; they cannot themselves be justified, at least in the manner appropriate to derivative propositions. For that reason it must seem to the committed idealist or sceptic that the defender of common sense begs the question" (Dennis C. Holt, in Dalgarno and Matthews 1989:147). But Reid's reply was that such exactly is the nature of a foundational presupposition: it can only be insisted upon. The realist presupposes that the world is real and comprehensible, whereas the skeptic presupposes that it is not. Therefore, the contest between realism and skepticism has to turn on considerations other than the choice or role of presuppositions.

(4) **Asking Once or Twice.** What is the basis for science's presuppositions? Reid's reply depended on whether that question was asked once or twice. Asked once, Reid supported science's presuppositions by an appeal to common sense. But if asked twice, the deeper issue became why the world was so constituted as common sense supposed. For instance, why does the physical world exist, rather than nothing? And why are we so constituted that the world is comprehensible to us?

Clearly, those deeper questions cannot be answered satisfactorily by a mere appeal to common sense but rather require the greater resources of some worldview. Regarding that deeper appeal to a worldview, Reid had two things to say.

First, Reid said that his own worldview, Christianity, explained and supported science's common-sense presuppositions. That worldview says that God made the physical world and made our senses reliable. "In Reid's doctrine the existence of common sense has theistic presuppositions; its truths are 'the inspiration of the Almighty.' Reid did not maintain that belief in them depends upon belief in

God; they are imposed upon us by the constitution of our nature, whatever our other beliefs. His implication is that we have to go behind common sense, if we are to explain its competence, to the fact that our nature has been constituted by God" [Selwyn A. Grave, in Edwards 1967(7):120–121].

Second, Reid claimed that virtually all other worldviews also respected the rudimentary common sense that provided science's presuppositions. Common sense was imposed on us "by the constitution of our nature," and that human nature was shared by all humans, regardless of whatever a person happened to believe or not believe about God.

Reid's strategy for supporting science's presuppositions had a wonderful clarity and balance. Worldview-independent, common-sense presuppositions preserved science's credibility. At the same time, there was no confusion or pretense that mere common sense provided a deep or ultimate explanation of why the world is as it is. That job has to be done by some worldview. Fortunately, although worldviews differ on many other points, they do not challenge each other over rudiments of common sense such as "The earth exists" or "I have two eyes." By seeing common sense as a penultimate rather than an ultimate defense of science, Reid invited the humanities to complement science's picture of the world.

(5) Reason's Double Office. Reid maintained that reason holds the traditional "double office" of "regulating our belief and our conduct" [Selwyn A. Grave, in Edwards 1967(7):121]. Belief and action should match. If not, the diagnosis is not the logical problem of incoherence between one belief and another contrary belief but rather the moral problem of insincerity or hypocrisy shown by mismatch between belief and action. As for the world of human actions, common sense was the only game in town. For example, a skeptic's mouth may say that we cannot be sure that a car is a real or hard object, but at a car's rapid approach, the skeptic's feet had better move!

Reid happily quoted Hume's own admission that a skeptic "finds himself absolutely and necessarily determined, to live and talk and act like all other people in the common affairs of life" (Hamilton 1872:485). Nevertheless, Hume went on to remark that "reason is incapable of dispelling these clouds" of skepticism. But if that was the case, it must be that Hume's version of reason held only the single office of regulating belief, rather than Reid's traditional reason that held the double office of regulating belief and action. In other words, only after first having adopted an impoverished notion of reason that pertains to belief but not to action is it possible for someone to regard as reasonable a skeptical philosophy that could not possibly be acted upon and lived out without jeopardizing the skeptic's survival. Greco provided a penetrating analysis of the key ideas in Reid's reply to the skeptics, and judged it extremely effective (John Greco, in Cuneo and van Woudenberg 2004:134–155).

Although regarded principally as a philosopher, Reid was also an accomplished scientist. He wrote and lectured on mathematics, optics, electricity, chemistry, astronomy, and natural history (Paul Wood, in Cuneo and van Woudenberg 2004:53–76).

Position papers from the American Association for the Advancement of Science (AAAS) provide a contemporary, mainstream expression of science's presuppositions. "Science presumes that the things and events in the universe occur in consistent patterns that are comprehensible through careful, systematic study. Scientists believe that through the use of the intellect, and with the aid of instruments that extend the senses, people can discover patterns in all of nature. Science also assumes that the universe is, as its name implies, a vast single system in which the basic rules are everywhere the same" (AAAS 1989:25). "All intellectual endeavors share a common purpose—making sense of the bewildering diversity of experience. The natural sciences search for regularity in the natural world. The search is predicated on the assumption that the natural world is orderly and can be comprehended and explained" (AAAS 1990:16).

Furthermore, careful scientific argumentation should disclose all premises. Indeed, the AAAS (1989:139) lists several "signs of weak arguments" that are useful for checking both others' and one's own arguments. One sign of a "shoddy" argument is that "The premises of the argument are not made explicit." Likewise, "Inquiry requires identification of assumptions" (NRC 1996:23). Therefore, science's presuppositions should be explicitly and fully disclosed.

The PEL model of full disclosure

A given scientific argument may be good or bad, and its conclusion may be true or false. But, in any case, the first step in assessing a scientific conclusion is merely to disclose the argument fully. Then, each and every piece of the argument can be inspected carefully and weighed intelligently, and every participant in the inquiry can enjoy clear communication with colleagues.

It is intellectually satisfying to be able, when need be, to present a scientific argument or conclusion with full disclosure. Also recall from Chapter 3 that the question "What goes in so that scientific conclusions can come out?" was asked by Aristotle and became the central question for the philosophy of science for two millennia. But, unfortunately, precious few scientists are trained to be able to answer that, the most elemental question that could possibly be asked about scientific inquiry.

What does it take to present a scientific conclusion with full disclosure? The basic model of scientific method presented in this book, named by the acronym the PEL model, says that presuppositions (P), evidence (E), and logic (L) combine to support scientific conclusions.

These three components interact so deeply that they must be understood and defined together. The situation is analogous to the three concepts of mothers, fathers, and children. It is easy to explain all three concepts together, but it would be impossible to give a nice explanation of mothers while saying nothing about fathers and children.

Remarkably, a simple example suffices to reveal the general structure of scientific reasoning, no matter how complex. Consider the following experiment, which you may either just imagine or else actually perform, as you prefer. Either envision or get an opaque cup, an opaque lid for the cup, and a coin. Ask someone else to flip the coin, without your observing the outcome or the subsequent setup. If the flip gives heads, place the coin in the cup and cover the cup with the lid. If the flip gives tails, hide the coin elsewhere and cover the cup with the lid. Now that the setup is completed, ask this question: "Is there a coin in the cup?"

The present assignment is to give a complete, fully disclosed argument with the conclusion that there is or is not a coin in the cup, as the case may be. This means that *all* premises needed to reach the conclusion must be stated explicitly, with nothing lacking or implicit. Before reading further in this section, you might find it quite instructive to write down your current answer to this problem for comparison with your response after studying this section.

To simplify the remaining discussion, the assumption is made that the actual state of affairs, to be discovered in due course through exemplary scientific experimentation and reasoning, is that "There is a coin in the cup." Those readers with this physical experiment before them may wish to make that so before proceeding with the assignment. Nevertheless, for purposes of the following story, we shall pretend that we do not yet know, and still need to discover, whether or not the cup contains a coin.

The question "Is there a coin in the cup?" can be expressed with scientific precision by stating its hypothesis set – the list of all possible answers. From the foregoing setup, particularly the coin flip, there are exactly two hypotheses:

H_1. There is a coin in the cup.

H_2. There is not a coin in the cup.

These two hypotheses are mutually exclusive, meaning that the truth of either implies the falsity of the other. They are also jointly exhaustive, meaning that they cover all of the possibilities. Consequently, exactly one hypothesis must be true.

How can we determine which hypothesis is true? The answer we seek is a contingent fact about the world. Thus, no armchair philosophizing can give the answer because nothing in the principles of logic or philosophy can imply that the cup does or does not contain a coin. Rather, to get an answer, we must look at the world to discover the actual state of nature. We must perform an experiment.

Various satisfactory experiments could be proposed. We could shake the cup and listen for the telltale clicking of a coin. We could take an X-ray photograph of the cup. But the easiest experiment is to lift the lid and look inside. Here, we presume a particular outcome, that we look and see a coin. That experimental outcome motivates the following argument and conclusion:

Premise. We see a coin in the cup.

Conclusion. There is a coin in the cup.

As a common-sense reply, this argument is superb, and its conclusion is certain that H_1 is true. Nevertheless, as a philosophical reply, this argument is incomplete and defective. Symbolize seeing the coin by "*S*" and the coin's existence in the cup by "*E*." Then this argument has the form "*S*; therefore *E*." It is a *non sequitur*, meaning that the conclusion does not follow from the premise. Something is missing, so let us try to complete this argument.

Another required premise is that "Seeing implies existence," or "*S* implies *E*," specifically for objects such as coins and cups. From the perspective of common sense, this is simply the presupposition that seeing is believing. In slightly greater philosophical detail, this premise incorporates several specific presuppositions, including that the physical world exists, our sense perceptions are generally reliable, human language is meaningful and adequate for discussing such matters, all humans share a common human nature with its various capabilities, and so on. The story of this premise can be told in versions as short or as long as desired.

With the addition of this second premise, the argument now runs as follows: "*S*; *S* implies *E*; therefore *E*." This is much better, following the valid argument form *modus ponens*. However, to achieve full disclosure, the logic used here must itself be disclosed by means of a third premise declaring that "*modus ponens* is a correct rule for deduction." Incidentally, to avoid a potential problem with infinite regress that philosophers have recognized for more than a century (Jeffreys 1973:198–200), note that here *modus ponens* is not being implemented in a formal system of logic but rather is merely being disclosed as a simple element in ordinary scientific reasoning.

Finally, a fourth premise is required. The "archive" is used as a technical philosophical term denoting all of a person's beliefs that are wholly irrelevant to a given inquiry. For example, given the current inquiry about a coin in a cup, my beliefs about the price of tea in China may be safely relegated to the archive. The archive serves the philosophical role, relative to a given inquiry, of providing for a complete partitioning of a person's beliefs. It also serves the necessary and practical role of dismissing irrelevant knowledge from consideration so that a finite analysis of the relevant material can yield a conclusion (whereas if one had to consider everything one knows before reaching a conclusion about the coin, no conclusion could ever be reached). For a particular scientific argument for a given person, each of that person's beliefs is one of the following: the argument's conclusion itself, or a presupposition, or an item of evidence, or a rule of logic, or an inert item in the archive.

Of course, to reside legitimately in the archive, a belief must be genuinely irrelevant and inert. Sometimes progress in science results from showing that a belief accidentally relegated to the archive is, in fact, relevant and must be exhibited as a presupposition, item of evidence, or logic rule. Anyway, a final premise is required here, saying that “the archive dismisses only irrelevant beliefs.” It contains nothing with the power to unsettle or overturn the current conclusion.

Rearranging the preceding four premises in a convenient order, they can now be collected in one place to exhibit the argument entirely, with full disclosure:

Premise 1 [Presupposition].	Seeing implies existence.
Premise 2 [Evidence].	We see a coin in the cup.
Premise 3 [Logic].	*Modus ponens* is a correct rule for deduction.
Premise 4 [Archive].	The archive dismisses only irrelevant beliefs.
Conclusion.	There is a coin in the cup.

This elementary argument exemplifies full disclosure according to the PEL model. It could be called the PELA model to recognize all four inputs, including the archive, but because the archive is essentially inert, I prefer the briefer acronym PEL that focuses on just the three active components. The formula of the PEL model is that presuppositions, evidence, and logic give the conclusion. This structure of a rational argument, flushed out by this simple coin example, pervades all scientific claims of knowledge about the world, regardless of how elementary or advanced. Figure 5.1 summarizes the components of the PEL model.

With this model, the basic nature of presuppositions can be understood clearly. A presupposition is a belief that is necessary in order for any of the hypotheses to be meaningful and true but that is nondifferential regarding the credibilities of the individual hypotheses. The hypotheses originate from the question being asked that is the ultimate starting point of an inquiry, and then presuppositions emerge from comparing the hypotheses to see what they all have in common. For example, in order to declare either H_1 or H_2 to be true, it must be the case that the physical world exists and that human sense perceptions are generally reliable. But these presuppositions are completely nondifferential, making H_1 neither more nor less credible than H_2.

Presuppositions also serve another role, limiting the hypothesis set to a finite roster of sensible hypotheses. Were common-sense presuppositions ignored, the foregoing hypothesis set with only two hypotheses, H_1 and H_2, might not be jointly exhaustive. Instead, it could be expanded to include countless wild possibilities such as H_3, that “We are butterflies dreaming that we are humans looking at a cup containing a coin.” But no empirical evidence could possibly discriminate among those three hypotheses, so this expanded hypothesis set would prevent science from reaching any conclusion. Numerous wild hypotheses, due to abandoning common-sense presuppositions, can undo science.

The PEL Model of Full Disclosure

Presuppositions + Evidence + Logic → Conclusions

Presuppositions are beliefs that are absolutely necessary in order for any of the hypotheses under consideration to be meaningful and true but that are completely non-differential regarding the credibilities of the individual hypotheses. Science requires several common-sense presuppositions, including that the physical world exists and that our sense perceptions are generally reliable. These presuppositions also serve to exclude wild ideas from inclusion among the sensible hypotheses under serious consideration.

Evidence is data that bear differentially on the credibilities of the hypotheses under consideration. Evidence must be admissible, being meaningful in view of the available presuppositions, and it must also be relevant, bearing differentially on the hypotheses.

Logic combines the presuppositional and evidential premises, using valid reasoning, to reach a conclusion. Science uses deductive and inductive logic.

A complete partitioning of a person's beliefs results from also recognizing an archive containing all beliefs that are irrelevant for a given inquiry, that is, beliefs that are not presuppositions or evidence or logic rules or conclusions. Irrelevant material must be ignored to avoid infinite and impossible mental processing. But the archive has no active role and hence is not indicated in the acronym for the PEL model.

Figure 5.1 Scientific conclusions emerge from three inputs: presuppositions, evidence, and logic.

Evidence has a dual nature, admissible and relevant. First, evidence is *admissible* relative to the available presuppositions. Hence, given common-sense presuppositions about the existence of the physical world and the general reliability of sense perceptions, it is admissible to cite the seeing of a coin; whereas without such presuppositions, such a claim would not be meaningful or admissible. Second, evidence is *relevant* relative to the stated hypotheses, bearing differentially on their credibilities. Hence, seeing a coin is relevant testimony because it bears powerfully on the hypotheses, making H_1 credible and H_2 incredible.

To avoid a possible embarrassment of riches, evidence can be further partitioned into two subsets: tendered evidence that is actually supplied, and reserved evidence that could be gathered or presented but is not because it would be superfluous. For example, before gathering any evidence whatsoever, the credibilities of hypotheses H_1 and H_2, that the cup does or does not contain a coin, can be represented by probabilities of 0.5 and 0.5. But, after tendering the evidence that "We see a coin in the cup," those probabilities become 1 and 0. After citing the additional evidence that "Shaking the cup causes a telltale clicking sound," those probabilities remain 1 and 0, as is still the case after also observing that "An X-ray photograph shows a coin inside the cup."

So, after initial evidence has already established a definitive conclusion, additional evidence has no further effect on the hypotheses' credibilities. At this point, wisdom directs us to close the current inquiry and move on to other pressing questions that are not yet resolved. Likewise, sometimes a conclusion will have reached a high probability of truth that may be considered adequate, even though more effort and evidence potentially could further strengthen the conclusion.

Comparing briefly, presuppositions answer the question: How can we reach any conclusion to an inquiry? But evidence answers the question: How can we assert one particular conclusion rather than another? For example, presuppositions about the existence of the physical world and the reliability of our sense perceptions are needed to reach any conclusion about a coin in the cup, whereas the evidence of seeing a coin in the cup supports the particular conclusion that there is a coin in the cup.

Logic serves to combine the premises to reach the conclusion. For example, the foregoing argument has the form "*S*; *S* implies *E*; therefore *E*," which follows the valid rule *modus ponens*. Finally, the archive serves to avoid infinite mental processing but does merit a check that its contents are truly irrelevant.

Note that the PEL model closely interlinks the concepts of presupposition, evidence, and logic. For example, half of the concept of evidence involves admissibility, which is determined by the presuppositions. Consequently, if one's concept of presuppositions is fuzzy, inexorably the concept of evidence will also be fuzzy, which will be disastrous. When presuppositions are not rightly understood, they become inordinately influential, suppressing the proper influence of evidence. Inquiry using the PEL model is depicted in Figure 5.2.

AAAS statements about the basic components of scientific thinking correspond with the PEL model proposed here. Evidence and logic are the most evident components: "The process [of scientific thinking] depends both on making careful observations of phenomena and on inventing theories for making sense out of those observations" (AAAS 1989:26; also see pp. 27–28 and AAAS 1990:16). Furthermore, the three inputs of the PEL model are brought together as the basis for scientific conclusions in the statement that "the principles of logical reasoning . . . connect evidence and assumptions with conclusions" (AAAS 1989:27), where "assumptions" here may be taken as a synonym for "presuppositions."

Finally, at most, a scientific argument may be correct; at the least, it should be fully disclosed. Full disclosure is the first and minimal requirement for clear scientific reasoning. Hence, when weighing scientific arguments and claims, it helps considerably to understand that when fully disclosed, *every* scientific conclusion emerges from exactly three inputs: presuppositions, evidence, and logic.

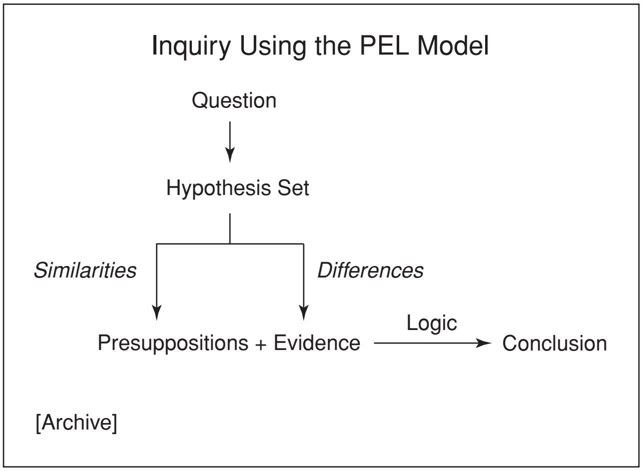

Figure 5.2 Scientific inquiry using the PEL model. Similarities among all of the hypotheses support presuppositions, whereas differences suggest potential evidence. Logic combines the presuppositions and evidence to reach the conclusion. Irrelevant knowledge is relegated to an inert archive.

Implementation of presuppositions

The method used here for implementing science's presuppositions proceeds in two steps. First, a little exemplar of common-sense knowledge about the world, called a "reality check," is selected that is as certain and universally known as is anything that could be mentioned. Second, philosophical reflection on this exemplar flushes out its presuppositions and reveals that they also suffice for scientific thinking.

The reason for choosing this particular method for implementing presuppositions is that it renders science's presuppositions as unimpeachable as our most certain knowledge. Science's presuppositions cannot be made unnecessary, but they can be made unproblematic. Also, this strategy fits historically with the thinking of many prominent scientists and mainstream philosophers. The text for the reality check, complete with its preamble, reads as follows:

> ***Reality Check***
> It is rational, true, objective, realistic, and certain that "Moving cars are hazardous to pedestrians."

To serve as a suitable object for philosophical analysis, however, it is essential that this text stand as common ground, believed by author and reader alike. So, do you believe this: that it is dangerous for pedestrians to step into the pathway of oncoming cars? I trust that this is the case. Indeed, readers who happen to have been star pupils in kindergarten will recognize this reality check as a sophisticated version of the command "Look both ways before crossing a road."

The choice, for or against accepting this reality check, is primordial and pretheoretical in that it is a common-sense conviction logically prior to all subsequent choices about the claims and methods of science. Common sense precedes science. Recall Reid's sentiment that the principles of common sense are older and of more authority than philosophy. Likewise, Wittgenstein insisted that rudimentary common-sense beliefs are oblivious to evidence because no evidence is more certain than such beliefs themselves: "my not having been on the moon is as sure a thing for me as any grounds I could give for it" (Ludwig Wittgenstein, in Anscombe and von Wright 1969:17e).

An appeal to common sense might be discredited or dismissed by a quick remark such as "Common sense isn't so common." Surely, this means that people sometimes spend more money than they earn, neglect the upkeep that could prevent costly repairs, and so on. But, clearly, my chosen exemplar of common sense is not gathered from the glorious heights of common sense, with offerings such as "Spend less than you earn" or "A stitch in time saves nine." Rather, "Moving cars are hazardous to pedestrians" is an exemplar of rudimentary common sense. So my appeal to rudimentary common sense should not be misinterpreted or dismissed as the unrealistic assumption that everyone is a paragon of good sense. Rather, it should be interpreted and taken seriously as the claim that all normal humans living on this one earth know some basics about physical reality.

In this academic book on scientific method, why fight for a meager scrap of common sense, that "Moving cars are hazardous to pedestrians"? What is the dreaded contrary of common sense? What is the threat?

Presumably, common sense's opponent is skepticism. But sincere skepticism is extremely rare. I, for one, have never met a single person who doubted, in any sense that could be taken as sincere, that "Moving cars are hazardous to pedestrians." Nor is it easy to imagine that such a person could survive apart from institutional care. Rather, the real opponent of common sense and science is ambivalent skepticism, which is common, just as is any other kind of inconsistency or insincerity.

The skeptical tradition, from start to finish, has been characteristically ambivalent. The founding figure of ancient Greek skepticism, Pyrrho of Elis, claimed not to trust his senses and once essayed to walk over a cliff, as if it could not matter. That sounds like gratifying, serious skepticism! But Pyrrho did that in the presence of his disciples, who kept their master from harm, and he lived to the ripe old age of ninety. He traveled to India with Alexander the Great.

The attempted coherence of the Pyrrhonistic skeptics is quite charming. Against the dogmatic Academic skeptics such as Sextus Empiricus, who claimed to show that knowledge was impossible, the Pyrrhonists claimed that they did not even know that they could not know. They were skeptical about whether or not they were skeptics! Much later, David Hume would continue that tradition of ambivalence, saying that the dictates of common sense must regulate ordinary daily life, even though they are not philosophically respectable.

A more recent example of that ambivalent tradition is Sir Karl Popper. On the one hand, some passages by Popper are reassuring to a common-sensical reader. He wrote of his "love" of common sense and said that "I am a great admirer of common sense" (Popper 1974:43, 1979:viii). Likewise, in his autobiography, in Schilpp (1974:71), Popper said that common-sense knowledge, such as "that the cat was on the mat; that Julius Caesar had been assassinated; that grass was green," is all "incredibly uninteresting" for his work because he focuses instead on genuinely "problematic knowledge" involving difficult scientific discoveries.

On the other hand, Popper wrote elsewhere that "The statement, 'Here is a glass of water' cannot be verified by any observational evidence" because of philosophical problems with induction and related matters that grip everyone, you and me included (Popper 1968:95). Now to say that you cannot know that "Here is a glass of water" is as plainly spoken a denial of common sense as to say that you cannot know my reality check that "Moving cars are hazardous to pedestrians." Clearly, common sense is under attack. But this attack is not consistent or sustained – nor could it be. Although Popper (1945:283) waxed eloquent about "the standards of intellectual honesty, a respect for truth, and . . . modest intellectual virtues," regrettably the force of such fine rhetoric is undercut by his saying elsewhere that trifling truths like "Here is a glass of water" are beyond a human's reach.

A discerning reader may detect the deep irony in Popper's declaration that *we* cannot know that "Here is a glass of water." His assumption that this incapacity afflicts all humans, rather than just him, requires knowing that all humans share similar endowments because of our common human nature. But with induction bankrupt according to Popper, how could he know this? Why is "Here is a glass of water" beyond reach, whereas "All humans share a common human nature" is within reach? The big "we" word is precisely what mainstream epistemology *is* entitled to, but skeptical epistemology *is not* entitled to.

The remedy for a disappointing, insincere skepticism is the sincere and cheerful acceptance of just one little scrap of common sense, such as that "Moving cars are hazardous to pedestrians." Reason must be restored to its double office of regulating both beliefs and actions. The insincere skeptic has a mouth whose words say that "Maybe cars are hazardous to pedestrians, and maybe not," but feet whose actions always say that "Moving cars are hazardous to pedestrians."

Like the declaration "I love you," the reality check can be voiced with varying degrees of conviction. Because of the frequent problems with superficial or ambivalent skepticism, the degree of conviction intended here must be made clear. Exactly which plaudits attend this reality check? To voice the reality check with clear conviction and to connect it with science's ambitions announced in Chapter 2, the reality check is proclaimed here with a preamble listing science's four bold claims: rationality, truth, objectivity, and realism. Furthermore, because this particular item of common-sense knowledge is so easy for all persons to learn and is absolutely exempt from sincere controversy, it is proclaimed here with one additional plaudit: certainty. It is voiced quite cheerfully with absolute confidence and unlimited boldness. It is voiced with no ambivalence, no superficiality, and no insincerity.

Given a nonnegotiable conviction that the reality check is true, what does this conviction imply for intellectual attacks on science's realism? It has a decisive implication, namely, any attack on science that also takes down common sense is simply incredible. Any attack that also targets common sense, including denying that we can know the reality check, fails because it does too much and thereby it loses credibility. Consequently, a legitimate attack on science's rationality must target science alone, not science and common sense both, as was emphasized in Chapter 4.

Having selected a little exemplar of knowledge about the world that is shared by author and reader alike, that "Moving cars are hazardous to pedestrians," the second and final step is philosophical reflection to disclose the presuppositions that are necessary for this reality check to be meaningful and true. "The logical premisses of factuality are not known to us or believed by us *before* we start establishing facts, but are recognized on the contrary *by reflecting on the way we establish facts*" (Polanyi 1962:162).

The presuppositions underlying the reality check can be organized in three broad groups: ontological, epistemological, and logical presuppositions. First, the ontological or metaphysical presuppositions include that physical reality has multiple things that are not all the same, such as cars that differ from pedestrians, or moving cars that differ from stationary cars. Because the universe is not merely one undifferentiated blob of being, there exists something to be comprehended. It also presumes that reality has natural kinds, to use the philosophical term. This means that multiple objects can be of the same kind (at a given level of description), such as numerous cats each being a cat. Human artifacts can also be of a given kind, such as numerous cars each being a car. One particularly important natural kind, from our perspective anyway, is the human being. The pedestrians or humans mentioned in the reality check share numerous properties, such as being soft and therefore vulnerable to strong impact from a large and hard object. It is not the case that car accidents are hazardous for some humans, whereas others are invincible. The reality check also presumes that physical reality is predictable. Its implicit advice not to step in front of a rapidly moving car obviously agrees with past experience regarding car accidents. But, equally, this advice is predictive, directed at preventing more accidents in the future.

Second, the epistemological presuppositions include that a human can know that an object is a rapidly approaching car and can act to move out of harm's way. This presupposes that our eyes, ears, and other sensory organs provide generally reliable information about the external world and that our brains can process and comprehend these sensory inputs. Furthermore, our brains can also direct our feet to move purposefully. Merely knowing without acting would not promote survival, so reason's double office of regulating belief and guiding action is evident. Another epistemological presupposition is that human language is meaningful. The reality check is expressed by several words in English. Humans have abilities of language and communication.

Third and finally, the logical presuppositions include coherence. To assert that "Moving cars are hazardous to pedestrians" legitimately, coherence demands that we not also assert the negation that "Moving cars are not hazardous to pedestrians." There is no credit for asserting the reality check if its opposite is also asserted. The reality check also presumes deductive and inductive logic. Logic is required to take a general principle and apply it to specific episodes of being near moving cars. Deduction is active in handling probability concepts, such as the idea of something being hazardous, meaning that harm is likely even if not certain. Induction is active in recognizing objects and in learning and using language.

The foregoing account of the reality check's presuppositions is not exhaustive. But, for most purposes, any further analysis would become technical and tedious. Furthermore, the presuppositions flushed out by analyzing this one representative little scrap of common sense, the reality check, pervade common sense. That is, philosophical analysis of "This cup contains a coin" or "Here is a glass of water" would evince the same presuppositions as this analysis of "Moving cars are hazardous to pedestrians." For any of these statements to be meaningful and true, the general makeup of ourselves and our world cannot follow just any conceivable story, but rather the world must be along the lines indicated by common-sense presuppositions. The following statement offers a concise expression of science's basic presuppositions:

> ***(Mainstream) science's basic presuppositions***
> The physical world is real and orderly and we humans find it substantially comprehensible.

The presuppositions pervading science cannot be less than those encountered in one little scrap of common sense. "Although through our [scientific] theories, and the instrument-aided observations they lead to, we can go beyond and correct some of the pretheoretical picture of the world we have by virtue of our being human, there is always going to be a sense in which all our knowledge and theory is based on elements in that [common-sense] picture.... More theoretical knowledge of the world is always going to have some connection, however remote, with the humdrum level if it is to count as science fact rather than science fiction" (O'Hear 1989:95–96).

On the other hand, some have argued that the presuppositions of science must be more than those of common sense, or else at least partially different. They claim that these extra presuppositions provide science with esoteric content that is wholly absent from common-sense knowledge and reasoning. For instance, science has overturned common sense with certain surprises: that the objects around us are mostly empty space and that the rate at which time passes by is not constant but depends on an object's speed relative to the observer. However, those surprises are conclusions of science, not presuppositions. Indeed, those discoveries were eligible to become conclusions precisely because they never were presuppositions. Those surprises were established by empirical evidence that counted as evidence precisely because common-sense presuppositions were in effect. Science can overturn common-sense expectations and beliefs, but not common-sense presuppositions.

Likewise, some have argued for additional presuppositions drawn from a particular worldview to really explain why the world is as it is. However, the position taken here follows the mainstream scientific tradition of seven centuries, which began with Albertus Magnus, of distinguishing penultimate and ultimate accounts of science's presuppositions. A penultimate account must be included in science's own business because these presuppositions are necessary to reach any conclusions. By contrast, pursuit of an ultimate account obliges science to enlist support from the humanities, so it seems wrongheaded to expect such an account from only science itself. Whereas there are many worldviews, there is only one common sense shared by all persons, including the ubiquitous belief that "Moving cars are hazardous to pedestrians." Therefore, invoking science's presuppositions by a penultimate appeal to common sense preserves science's objective and public character.

In conclusion, if you believe the reality check, that "Moving cars are hazardous to pedestrians," then you have already adopted all of the presuppositions needed for science to flourish. You have already delivered science from the specter of skepticism. Compared with common sense, science requires more experimentation, data, reasoning, and work but absolutely nothing more by way of presuppositions. Building science on a base of common sense is a plausible and respected tradition (Nash 1963:3–62). According to Einstein, "The whole of science is nothing more than a refinement of everyday thinking" (Einstein 1954:290).

Science's worldview forum

If this book were claiming to address proponents of *every* worldview, including skepticism, then it would not be fair or correct to pretend that the preceding reality check is shared knowledge. Skepticism and the reality check are incompatible. If skepticism is true, then the reality check with its grand preamble is definitely unwarranted; but if the reality check is true, then skepticism is false. So something must go. My choice is to hold on to the reality check, accepting the consequence that this limits the range of worldviews engaged here.

This book's project is to presuppose common sense and then build scientific method, not to refute the skeptic and thereby establish common sense. The skeptic is unanswered here, not because of ill will on my part, but simply because I do not know what a skeptic wants from a nonskeptic or realist such as myself.

Fortunately, real skeptics are quite rare. My university work, including professional meetings of scientific and philosophical societies, causes me to meet many people from many nations. However, I have not yet personally met one real skeptic. Or, to be a little more accurate, I have met some people with skeptics' mouths but have not encountered any skeptics' feet. Their mouths may counter the reality check, saying it is uncertain; but their feet obey it with all diligence, as their survival attests. "Skeptics are like dragons. You never actually meet one, but keep on running across heroes who have just fought with them, and won" (Palmer 1985:14).

Realists may be perplexed that skepticism tends to be such an extreme position as to reject even the simple reality check. Recall, for instance, that Popper (1968:95) judged that even the simple common-sense belief that "Here is a glass of water" lies outside the bounds of human competence. But that extremism has a logical explanation. Imagine that you and I are enjoying lunch and beer at a pub. Suddenly, I am struck with remorse that I have never experienced being a skeptic and forthwith give it my best attempt. After struggling manfully for an hour, I proudly exclaim, "I've got it; I doubt that this salt shaker exists! Everything else still exists, but this salt shaker is gone – clean gone!" Understanding that I have lived for decades without the slightest inclination toward skepticism, doubtless your charity will move you to praise my fledgling skepticism. Nevertheless, you might be sorely tempted to say something like, "Well, let me move this pepper shaker that you can see right next to the salt shaker that you cannot see. Now can you see them both?" The same embarrassment would attend any other modest version of skepticism, such as doubting my beer but not yours, or doubting one chair in the pub but not anything else. Only the radical doubt of everything leaves no easy refutation close at hand.

The dismissal of skepticism has implications for worldviews. A worldview is a person's beliefs about the basic makeup of the world and life. Depending on a person's intellectual maturity, a worldview may be more or less explicit, articulate, and coherent. But everyone has a worldview. It supplies answers to life's big questions, such as: What exists? What can we know? What is good, true, and beautiful? What is the purpose of human life? What happens after death? Many worldviews are rooted in a religion or a philosophical position, but some persons hold views not affiliated with any widespread movement. There are many minor worldviews but relatively few major ones. The world's population, currently more than 7 billion persons, is approximately 32% Christians, 19% Muslims, 19% atheists, 14% Hindus, 9% tribal or animist religions, 6% Buddhists, and 1% other, which includes 0.3% Jews.

The most significant question that can be asked about worldviews is: Which one is true? However, that is not this book's question. Rather, this book is about scientific method, so its question is: How much does worldview pluralism affect science's claims and fortunes? It is simply a fact of life that historically there have been diverse views and that worldview pluralism is likely to continue for the foreseeable future. Is this a problem for science, or not? Does worldview diversity present insurmountable problems, motivating separate versions of science for each worldview, or even rendering science invalid for adherents of some worldviews? Or can science, preferably in one single version, work for essentially everyone, including atheists, Hindus, Buddhists, Jews, Christians, Muslims, and others?

The answer offered here is that a single version of science works fine for nearly every worldview, but not quite all. Science works in all worldviews that cheerfully assert the reality check, but it fails in all those that reject the reality check. Accordingly, science's worldview forum is comprised of all worldviews that assert the reality check.

Science could not be objective and public if science needed to depend on controversial philosophies or specific cultures. Fortunately, underneath these philosophical and cultural differences, there exists on this one earth a single human species with a shared human nature, and that commonality provides adequate resources for science's common-sense presuppositions. "Cultures may appear to differ, but they are all rooted in the same soil. . . . Human nature precedes culture and explains many of its features" (Roger Trigg, in Brown 1984:97).

Justification of knowledge claims

Besides the reality check itself, additional beliefs have also been deemed equally certain here, including the experimental result that "There is a coin in the cup." Likewise, Wittgenstein judged "the existence of the apparatus before my eyes" to have the same certainty as "my never having been on the moon" (Ludwig Wittgenstein, in Anscombe and von Wright 1969:43e). Such thinking – that various beliefs are equally certain – is intuitively appealing and undoubtedly right. This section formalizes that intuition.

Precisely what philosophical reasoning can be given for deeming various beliefs to be certain? How does the reality check's assumed certainty extend to other beliefs' demonstrated certainty? To make these questions more concrete, consider the belief that "There are elephants in Africa." What formal, philosophical account could be given for judging this belief to be certain? Prior to reading the rest of this section, I recommend that the reader try on his or her

A Model of Justification

Reality Check. Adopt as realistic, true, and certain the reality check's belief, denoted by A, that "Moving cars are hazardous to pedestrians."

Certainty Equivalence. Demonstrate that the belief, denoted by B, has certainty equivalence with the beliefs in the reality check, denoted by A.

This demonstration requires:

(1) the same presuppositions,
(2) equally admissible, relevant, and weighty evidence,
(3) equally valid or correct logic, and
(4) an equally inert and dismissible archive.

Rule for Justification. From the above beliefs, that A is certain and that A has certainty equivalence with B, infer that B is certain.

Figure 5.3 A model for justifying scientific beliefs based on the reality check, certainty equivalence, and rule for justification.

own to construct a philosophically rigorous proof that "There are elephants in Africa" is true and certain. The method of justification offered here has three steps, as depicted in Figure 5.3.

The first step merely reasserts the reality check's claim of certainty, denoted by belief *A*. The second step draws upon the PEL model to demonstrate that another belief *B* has the same certainty as belief *A*. This demonstration requires (1) the same presuppositions; (2) equally admissible, relevant, and weighty evidence; (3) equally valid or correct logic; and (4) an equally inert and dismissible archive. Then, the third and final step is a rule for justification that infers from the above premises, that *A* is certain and that *A* has certainty equivalence with *B*, that the conclusion *B* is certain.

For example, this model of justification can be applied to Africa's elephants as follows. Denote "Moving cars are hazardous to pedestrians" by *A*, and "There are elephants in Africa" by *B*. First, the reality check is asserted to be certain: *A* is certain. Second, the same presuppositions are necessary and sufficient to believe *A* or *B*; recent sightings or photographs of elephants in Africa are as admissible, relevant, and weighty as any evidence from sightings or photographs of car accidents with pedestrians that could be adduced for the reality check; equally valid or correct logic works in both cases; and both cases generate equally inert and dismissible archives. Thus, *A* has certainty equivalence with *B*. Third and finally, applying the rule for justification to these two premises produces the conclusion, "It is certain that 'There are elephants in Africa.'" The only way to unsettle the conviction that “There are elephants in Africa” would be to embrace such profound skepticism as would also unsettle the reality check that “Moving cars are hazardous to pedestrians.”

This model of justification explains the simple case of deeming other beliefs to be certain. However, much knowledge is probabilistic, such as a forecast that rain is likely tomorrow. This model is easily extended to justify probabilistic as well as certain conclusions, but probabilistic reasoning is better left to Chapters 8 and 9 on probability and statistics. The crucial move for justifying a probabilistic conclusion is to accept common-sense presuppositions so that the conclusion faces only the ordinary and workable challenge of imperfect evidence but not the insurmountable and debilitating challenge of skeptical presuppositions.

Review of functions

The role of presuppositions in scientific thinking is difficult to fully grasp because presuppositions serve so many functions. This chapter reveals at least these seven functions: Presuppositions are essential for reaching any scientific conclusions, for full disclosure of arguments, for rendering evidence admissible, for interconnecting science and common sense, for defending science’s rationality, for framing sensible questions that eliminate wild hypotheses, and for demarcating science’s worldview forum.

Yet the most vital function of presuppositions is to specify science’s referents, that is, what science is referring to or talking about. Consider the following thought experiment. Imagine that the contemporaries Berkeley, Hume, and Reid were brought together and were all patting a single horse. All three would report the same experience of a big furry animal, but their interpretations of that experience would differ. Berkeley would say that the physical horse does not exist but only the mind’s idea of a horse. Hume would say that science should concern our experience of the horse but would not say that the horse does or does not exist. Reid would say that philosophy and science should follow common sense with a confident and cheerful certainty that the physical horse does exist. Likewise, imagine stepping further back in the history of this debate and seeing the contemporaries Plato and Aristotle patting a single dog. For Plato, the dog would be but an illusory and fleeting shadow of its inaccessible but thoroughly real Form. But, for Aristotle, the dog itself would be accessible to our sensory experience and would be completely real. Clearly grasp that this perennial debate is not about the sensory data as such but rather is about the metaphysical interpretation of that data. This debate is altogether about philosophical presuppositions concerning what is real and knowable and is altogether not about scientific evidence.

Mainstream science follows common sense in presupposing that the physical world is real and orderly and we humans find it substantially comprehensible.

And mainstream science follows mainstream philosophy in granting reason the double office of regulating belief and action, thereby fostering sincerity and confidence.

Summary

By perceiving science's presuppositions, scientists can understand their discipline in greater depth and offer scientific arguments with full disclosure. An inquiry's presuppositions are those beliefs held in common by all of the hypotheses in the inquiry's hypothesis set. Analysis of a single scrap of common sense, such as the reality check that "Moving cars are hazardous to pedestrians," suffices to flush out the presuppositions that pervade common sense and science alike. Mainstream science's basic presuppositions are that the physical world is real and orderly and we humans find it substantially comprehensible.

Aristotle clearly accepted science's ordinary, common-sense presuppositions, but his deductivist vision worked better for mathematical sciences than for natural sciences. Albertus Magnus resolved that deficiency by conditional or suppositional reasoning, granting the natural sciences definitive empirical evidence on the supposition of common-sense presuppositions. That device also granted science substantial independence from philosophy and theology, a view subsequently endorsed by Aquinas, Duns Scotus, Buridan, and others. A tremendous diversity of views on science's presuppositions and claims emerged from the work of Francis Bacon, Berkeley, Hume, and Reid. The AAAS affirms science's common-sense presuppositions.

The PEL model of full disclosure shows that scientific method amounts to disclosing and securing the presuppositions, evidence, and logic needed to support scientific conclusions. Presuppositions are disclosed and legitimated by a procedure with two steps. First, a reality check is adopted by faith and with sincerity and confidence, that "Moving cars are hazardous to pedestrians." Second, philosophical reflection on this reality check reveals its ontological, epistemological, and logical presuppositions. The most obvious presuppositions are that the physical world exists and that our sense perceptions are generally reliable.

Insistence on a nonnegotiable reality check causes science's worldview forum to include all worldviews accepting this reality check, but to dismiss radical skepticism. This book's project is to presuppose common sense and then build scientific method, not to refute the skeptic and thereby establish common sense.

Knowledge claims are justified by asserting the reality check's certainty and then, in light of the PEL model, demonstrating that other beliefs have (1) the same presuppositions; (2) equally admissible, relevant, and weighty evidence; and (3) equally valid or correct logic (and an equally inert and dismissible archive). An example was given of justifying the common-sense belief that there are elephants in Africa. This model of justification for certain conclusions is readily extended to probable conclusions by adding probability theory and statistical analysis.

Presuppositions serve many functions in scientific thinking, being absolutely indispensable for reaching any conclusions whatsoever. The most vital function of presuppositions is to specify what science is talking about, namely the real, orderly, and comprehensible world engaged by mainstream science.

Study questions

(1) What are science's presuppositions? The text argues that science needs just common-sense presuppositions, nothing less and nothing more. What would be your best arguments for a different position, contrary to the text?

(2) The text implements science's presuppositions by a two-step procedure: adoption of a common-sense reality check, followed by philosophical reflection on its content. But often there are many ways to get a job done. Can you suggest an alternative implementation? What advantages or disadvantages does that alternative have over the recommended implementation?

(3) Presuppositions have the crucial role of supplying a necessary input for reaching any conclusions whatsoever. What other roles do presuppositions have?

(4) Explain the distinction between an ultimate and penultimate account of science's presuppositions. The text claims that a penultimate account, operating by an appeal to a worldview-independent and shared common sense, is the proper and sufficient business of science itself; whereas an ultimate account requires additional resources from the humanities, and hence is outside the purview of a book or course on scientific method. Do you agree or disagree? How would you argue for your position?

(5) Consider the scientific conclusion: The sun's mass is about 2×10^{30} kilograms. How would you apply the model of justification to this conclusion?

6

Science's powers and limits

What are science's powers and limits? That is, where is the boundary between what science is and is not able to discover? The American Association for the Advancement of Science has identified that issue as a critical component of science literacy: "Being liberally educated requires an awareness not only of the power of scientific knowledge but also of its limitations," and learning science's limits "should be a goal in all science courses" (AAAS 1990:20–21). The National Research Council concurs: "Students should develop an understanding of what science is, what science is not, what science can and cannot do, and how science contributes to culture" (NRC 1996:21).

People's motivations for exploring the limits of science can easily be misconstrued, so they should be made clear from the outset. Unfortunately, for some authors writing about science's limits, the motivation has been to exaggerate the limitations in order to cut science down, support antiscientific sentiments, or make more room for philosophy or religion. For others, the motivation has been to downplay science's limitations in order to enthrone science as the one and only source of real knowledge and truth. Neither of those excesses represents my intentions. I do not intend to fabricate specious problems to shrink science's domain, nor do I intend to ignore actual limitations to aggrandize science's claims. Rather, the motivation here is to characterize the actual boundary between what science can do and cannot do. One of the principal determinants of that boundary is the topic of this book, the scientific method.

Rather obvious limitations

Several limitations of science are rather obvious and hence are not controversial. The most obvious limitation is that scientists will never observe, know, and explain everything about even science's own domain, the physical world. The Heisenberg uncertainty principle, Gödel's theorem, and chaos theory set fundamental limits.

Besides these fundamental limits, there are also practical and financial limits. "Today, the costs of doing scientific work are met by public and corporate funds. Often, major areas of scientific endeavor are determined by the mission-oriented goals of government, industry, and the corporations that provide funds, which differ from the goals of science" (AAAS 1990:21).

The most striking limitation of science, already discussed in Chapter 5, is that science cannot prove its presuppositions. Nor can science appeal to philosophy to do this job on its behalf. Rather, science's presuppositions of a real and comprehensible world – as well as philosophy's presuppositions of the same – are legitimated by an appeal to rudimentary common sense followed by philosophical reflection.

However, the remainder of this chapter explores the powers and limits of science that are not especially obvious. Science's capacity to address big worldview questions is important but controversial. And an integrally related matter is the role of the humanities and the influence of individual experience on worldview convictions. A neglected topic meriting attention is science's power to enhance personal character and experiences of life.

The sciences and worldviews

Can science reach farther than its ordinary investigations of galaxies, flowers, bacteria, electrons, and such? Can science also tackle life's big questions, such as whether God exists and whether the universe is purposeful? This is the most complex – and perhaps the most significant – aspect of the boundary between science's powers and limits.

Life's grand questions could be termed religious or philosophical or worldview questions. But a single principal term is convenient and the rather broad term *worldview* is chosen here. A worldview sums up a person's basic beliefs about the world and life. The following account draws heavily from Gauch (2009a, 2009b).

Whether worldview implications are part of science's legitimate business is controversial. Nevertheless, the mainstream view, as represented by the AAAS, is that one of science's important ambitions is contributing to a meaningful worldview. "Science is one of the liberal arts" and "the ultimate goal of liberal education" is the "lifelong quest for knowledge of self and nature," including the quest "to seek meaning in life" and to achieve a "unity of knowledge" (AAAS 1990:xi, 12, 21). AAAS position papers offer numerous, mostly helpful perspectives on religion, God, the Bible, clergy, prayer, and miracles. The Dialogue on Science, Ethics, and Religion (DoSER) program of the AAAS offers ongoing events and publications.

The AAAS regards science's influence on worldviews not only as a desirable quest but also a historical reality. "The knowledge it [science] generates sometimes forces us to change—even discard—beliefs we have long held about ourselves and our significance in the grand scheme of things. The revolutions that we associate with Newton, Darwin, and Lyell have had as much to do with our sense of humanity as they do with our knowledge of the earth and its inhabitants.... Becoming aware of the impact of scientific and technological developments on human beliefs and feelings should be part of everyone's science education" (AAAS 1989:134). Likewise, "Scientific ideas not only influence the nature of scientific research, but also influence—and are influenced by—the wider world of ideas as well. For example, the scientific ideas of Copernicus, Newton, and Darwin... both altered the direction of scientific inquiry and influenced religious, philosophical, and social thought" (AAAS 1990:24).

But, unfortunately, on the specific worldview question of life's purposes, AAAS position papers are inconsistent. On the one hand, they say that science *does not* answer the big question about purposes: "There are many matters that cannot usefully be examined in a scientific way. There are, for instance, beliefs that—by their very nature—cannot be proved or disproved (such as the existence of supernatural powers and beings, or the true purposes of life)" (AAAS 1989:26). On the other hand, it is most perplexing that another AAAS position paper claims that science *does* answer this question: "There can be no understanding of science without understanding change and the fact that we live in a directional, though not teleological, universe" (AAAS 1990:xiii; also see p. 24). Now "teleological" just means "purposeful," so here the AAAS is boldly declaring, without any argumentation or evidence, that we live in a purposeless universe. Consequently, this is one of those rare instances in which AAAS statements have not provided reliable guidance because they are contradictory.

Science's powers and limits as regards ambitious worldview inquiries depend not only on science's method but also on social conventions that define science's boundaries and interests. A social convention prevalent in contemporary science, *methodological naturalism*, limits science's interests and explanations to natural things and events, not supernatural entities such as God or angels. Methodological naturalism has roots in antiquity with Thales (*c.* 624–546 BC) and others. Subsequently, medieval scholars emphasized pushing their understanding of natural causes to its limits (Lindberg 2007:240–241; Ronald L. Numbers, in Lindberg and Numbers 2003:265–285). But the name "methodological naturalism" is of recent origin, only three decades ago.

Methodological naturalism contrasts with metaphysical or *ontological naturalism* that asserts natural entities exist but nothing is supernatural, as claimed by atheists. Hence, methodological naturalism does not deny that the supernatural exists but rather stipulates that it is outside science's purview. Unfortunately, methodological naturalism is sometimes confused with ontological naturalism. To insist that science obeys methodological naturalism *and* that science supports atheism is to get high marks for enthusiasm but low marks for logic.

Many worldview matters might seem to reside within science's limits, rather than its powers, given that methodological naturalism excludes the supernatural. Indeed, questions such as whether God exists and whether the universe is purposeful, which inherently involve the supernatural, are precisely the kinds of questions that are foremost in worldview inquiries.

However, to be realistic, contemporary science is replete with vigorous discussions of worldview matters. For starters, consider the exceptional science books that manage to become bestsellers. The great majority of them are extremely popular *precisely because* they have tremendous worldview import, such as Collins (2006) and Dawkins (2006). Less popular but more academic books also concern science and worldviews, such as Ecklund (2010).

Furthermore, interest in science's worldview import is a minor but consistent element in mainstream science journals. For instance, religious experience provides one of the standard arguments for theism, but in *American Scientist*, psychologist Jesse Bering (2006) attempted to explain away belief in a deity or an afterlife as a spurious evolutionary by-product of our useful abilities to reason about the minds of others. Likewise, Michael Shermer, the editor of *Skeptic*, has a monthly column in *Scientific American* with provocative items such as "God's number is up" (Shermer 2004). Also, survey results on the religious convictions of scientists were published in *Science* (Easterbrook 1997), and significant commentary on science and religion was provided in *Nature* (Turner 2010; Grayling 2011; Waldrop 2011). To gauge the extent of worldview interests in mainstream science, an interesting little exercise is to visit the websites of journals such as *Nature* and *Science* and search for "religion" to see how many thousands of hits result.

Hence, contemporary scientific practice is far from a consistent and convincing implementation of methodological naturalism. Nor is the present scene uncharacteristic, given the broad interests of natural philosophers (now known as "scientists" since around 1850) in ancient, medieval, and modern times. Of course, methodological naturalism is characteristic of routine scientific investigations, such as sequencing the genome of the virus that causes the common cold, but that does not necessarily mean that it extends to every last scientific interest or publication.

Whereas mainstream science can and does have some worldview import, prominent variants of fringe science are problematic, particularly scientism and skepticism. They are opposite errors. At the one extreme, scientism says that only hard, no-nonsense science produces all of our dependable, solid truth. At the opposite extreme, skepticism says that science produces no final, settled truth.

Yet, curiously, these opposite errors support exactly the same verdict on any worldview inquiry appealing to empirical and public evidence. On the one hand, scientism automatically and breezily dismisses any worldview arguments coming from philosophy, theology, or any other discipline in the humanities because such disciplines lack the validity and authority that science alone possesses. On the other hand, after skepticism has already judged all science to be awash in uncertainty and tentativeness, ambitious worldview inquiries are bound to receive this same verdict of impotence.

Returning to mainstream science, some scientists explore science's worldview import, other scientists exclude worldview issues in the name of methodological naturalism, and still other scientists have no interests or opinions on such matters whatsoever. This diversity of interests and temperaments hardly seems surprising.

Empirical method in the humanities

This whole book is about scientific method, but this one section is about a broader topic that may be termed *empirical method*, which subsumes scientific method as a special case. Empirical method concerns what can be known by means of empirical and public evidence, regardless of whether that evidence comes from the sciences or the humanities. Any persons interested in pushing empirical and public evidence to its limits must understand the structure and workings of empirical method, not merely scientific method.

The humanities are academic disciplines that study the human condition. They include the classics, languages, literature, history, law, philosophy, religion or theology, and the visual and performing arts. The humanities use a great variety of methods, including some use of empirical and public evidence.

The essence of scientific method is to appeal to empirical and public evidence to gain knowledge of great theoretical and practical value about the physical world. In greater detail than that single sentence can capture, this book's account of scientific method features the PEL model of full disclosure and the justification of truth claims based on that model, as summarized in Figures 5.1 and 5.3 – although this whole book is needed for a reasonably complete account of scientific method. But, clearly, empirical and public evidence also has roles in the humanities. Especially when empirical evidence is used in ambitious worldview inquiries, as contrasted with routine scientific or technological investigations, the combined perspectives of the sciences and the humanities yield the most reliable and beneficial results.

This section's extremely brief account of empirical method is relevant in this book on scientific method for at least three reasons. First, understanding how public evidence and standard reasoning support truth claims in multiple contexts across the sciences and the humanities gives students their best chance of deeply understanding rationality within science itself. Comparing and contrasting stimulates real comprehension. Second, the AAAS (1990) vision of science as a liberal art calls for a humanities-rich understanding of science, which is promoted greatly by grasping the empirical method that spans the sciences