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.
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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.
(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
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General Principles

Principles of Science

Principles of Rationality

Wellsprings of Common Sense

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.
A controversial idea

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
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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:xi; 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
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: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