Thinking about Science

Good Science, Bad Science, and How to Make It Better

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Preface

We live in an age of science and technology. Science has allowed us to understand our place in the universe and our relationship to all life on Earth. Technology has provided a sophisticated computer on which to compose this book and allowed us to reshape our world to make life safer, more productive, and more comfortable. This has never been clearer than during this time of plague, as the COVID-19 pandemic enters its fourth year and finally shows signs of receding. The advanced technology of COVID-19 vaccines has greatly reduced the mortality of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) infection and provided a vivid demonstration of the tangible benefits of science for society. As harrowing as the last few years have been, just think of what they would have been like *if we didn't have science*.

And yet, there are signs that not all is well with the scientific enterprise. The pace of transformative biomedical innovation appears to be slowing (1, 2). Fraud, sloppiness, and error have required the retraction of publications from the literature. Record numbers of research trainees are opting out of academic career pathways. Surveys report declining public confidence in scientists. With looming challenges from future pandemics, climate change, and shortages of food, water, and energy, it is vital for the world's scientific enterprise to be firing on all cylinders, to use an automotive metaphor (which will happily become anachronistic as electric vehicles displace those with internal combustion engines). This volume is a collection of essays exploring the nature of science and the way that it is performed today. In thinking about science, both good and bad, we will cast a light on contemporary scientific culture and practice, provide guideposts for young scientists, and propose a blueprint for reforming the way that science is done.

This book is written for scientists and science students, but also for technologists, engineers, mathematicians, teachers, journalists, administrators, policymakers, and anyone with an interest in science and how scientists think. The project began 15 years ago when we were editors at the journal *Infection and Immunity*. Our initial collaborative essay, called "Descriptive Science," was prompted by the tendency of many reviewers to dismiss work with the adjective "descriptive," despite the fact that *description* is the foundation of much of science (3). Encouraged by the positive responses from our colleagues, we subsequently collaborated on more than 40 articles, editorials, or commentaries. Many of the essays in this collection had their genesis in conversations or email exchanges, which eventually developed into editorials or commentaries. Each has been recently updated and supplemented with additional material for publication in this book. Nine of the chapters are completely new and have not been published elsewhere.

Our goal has been to create a volume that can be read either sequentially or as individual chapters, each constituting a freestanding essay that can be read and understood independently, although we have connected the themes through cross-referencing. Anyone reading the book from cover to cover will note some repetition, as certain issues arise again and again in various contexts. This is intentional and was necessary for the chapters to be able to stand on their own. We hope that this will help to reinforce these points.

Over the years, we have often commented to each other how writing these essays has improved our understanding of science and made us better scientists. We hope the same will be true for our readers. You will find that much of the material is slanted toward issues in the biomedical sciences, with a particular preference for the subdisciplines of microbiology and immunology. This reflects the fact that we are both active scientists with research programs focused on microbial pathogenesis. We make no apologies for writing about what we know best and note that other science essayists, such as Thomas Kuhn (4) and Eugene Wigner (5) writing about scientific revolutions and the unreasonable effectiveness of mathematics, have focused largely on examples from the physical sciences. In fact, we think that our biomedical emphasis makes sense since the 21st century is heralded to be the biological century. We subscribe to the view that science is a continuous discipline and observations made in one domain can apply to other domains as well. Nevertheless, we have attempted whenever possible to bring the physical sciences into the context of our essays, and readers will find numerous references to Newtonian physics, plate tectonics, and particle physics. We purposefully refer to some of the same scientific discoveries in multiple chapters in order to illustrate the continuity of themes across different aspects of science using familiar examples. Hence, some scientists, such as Alfred Wegener, Oswald Avery, and Rosalind Franklin, appear in more than one chapter, and we hope you will enjoy becoming more acquainted with them.

In many ways, *Thinking about Science* is a commentary on the current state of science in the early 21st century, with a particular emphasis on biomedical research. Although both of us are unabashed admirers of science and the scientific process, the reader may note a critical tone in many of these chapters. This, too, is intentional and reflects the fact that many chapters are written to highlight a problem in science in the hope of correcting it. The "Historical Science" chapter laments how often science ignores and neglects its history. In fact, we hope that the book provides an accurate snapshot, from the perspective of scientists working in the present day, for future historians of science. Similarly, we hope that chapters such as "Descriptive Science," "Mechanistic Science," "Reductionistic and Holistic Science," and "Important Science" have captured the tension of our time regarding preferred scientific approaches. "Impacted Science" describes a contemporary sociological malady that we hope will become obsolete in future years as science reforms its value system. "Dismal Science" delves into the economics of science, and we hope that more economists will take an interest in this important topic that remains largely unexplored. "Plague Science" feels unfinished, as every week brings a new development in the COVID-19 pandemic, and yet we hope that the words therein capture a sense of this moment in early 2023 by documenting successes and failures in confronting a novel viral scourge. In updating the early chapters of our collaboration, we have been both pleasantly surprised at the progress in certain areas, such as prepublication review, efforts to improve reproducibility, and efforts to improve equality and diversity in science, and dismayed by how little has been done in others, such as persistent problems with peer review and funding.

For us, this book has provided an opportunity to reflect and to gather and update our thoughts after 15 years of friendship and collaboration. This is, of course, a work in progress, and we will continue our work as practitioners, observers, and commentators of contemporary science who want to improve the scientific enterprise. We encourage readers to write to us with their comments, criticisms, and suggestions so that we can continue to think about science together.

January 2023

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I

DEFINITIONS OF SCIENCE

1 What Is Science?

Science is not inevitable; this question is very fruitful indeed.

Edgar Zilsel (1)

Science is humanity's greatest invention. When difficult decisions are to be made, everyone says that they want to "follow the science." But what is science? The Merriam-Webster online dictionary defines science as "knowledge about the natural world based on facts learned through experiments and observation" (2). The word itself is derived from the Latin word *scientia*, which means "knowledge." However, as Carl Sagan observed, "Science is more than a body of knowledge. It is a way of thinking" (3). Thus, Great Britain's Science Council has defined science as "the pursuit and application of knowledge and understanding of the natural and social world following a systematic methodology based on evidence" (4). This is an improvement, but perhaps goes too far in emphasizing the process over scientific knowledge itself.

Thomas Huxley suggested that science is merely "common sense clarified" (5), although common sense tells us many things that science has shown to be untrue, such as that the Sun travels around the Earth (6). Science rises beyond mere observation, intuition, and association. Science is a way of acquiring knowledge that is progressive, cumulative, testable, and predictive. Fields that call themselves sciences share certain elements in common, including facts, theories, methods, practices, and predictions. The most persuasive characteristic of science is that it

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works. Science underlies all technology, from the light-emitting diode illuminating this room to the laptop on which this chapter is being composed, or the cellphone giving a reminder about an imminent meeting. Yet science is much more than technology, and its relationship to technology is complex (Box 1.1). Science allows the recognition of principles that make the natural world comprehensible. That doesn't mean that science is always right, not by a long shot. Scientific knowledge is always tentative and subject to change. But evidence of the power of the scientific method is all around us, and even when science leads to errors, the method itself embodies the means to correct its mistakes.

The scientific method was not invented all at once, but rather evolved over time with refinement from a range of sources. The scientific method has not arisen in every civilization. In fact, most scientific knowledge has been acquired only during the past 400 years, less than one-quarter of 1% of the time that our species has

Box 1.1 Science and technology

Science and technology are often mistakenly viewed as synonymous. Whereas a definition of science is elusive, the definition of technology is easier. Technology is "the application of scientific knowledge for practical purposes" (24). Hence, while science and technology are intimately associated, the two can exist independently. For example, the ancient world had the technology to construct majestic buildings and structures such as pyramids and the Great Wall of China without a formal understanding of the laws of physics. The Industrial Revolution was catalyzed by the invention of the steam engine, which was created by tinkering without any knowledge of thermodynamics. In fact, the field of thermodynamics emerged afterwards to explain phenomena observed in steam engines and in efforts to optimize their efficiency. On the other hand, major advancements in science often find no immediate technological applications. Einstein's theory of general relativity, formulated in 1916, did not find a clear technological application until the development of a geopositioning system in the 1970s required synchronization of clocks on Earth and in orbit, which run differently depending on the gravitational field that they experience. In 2016, gravitational waves were first detected using remarkable technology in the form of paired interferometers, constructed by highly exacting tolerances prescribed by physical laws, but these have yet to find a technological application. Today, much scientific research is dependent on technology made possible by our scientific knowledge.

inhabited the earth. In their books *The Unnatural Nature of Science* and *Uncommon Sense*, the embryologist Lewis Wolpert and the physicist Alan Cromer, despite their different perspectives, both trace the origins of science to ancient Greece (6, 7). Plato regarded reason as the most powerful capacity of human beings, Thales of Miletus attempted to describe the nature of the world, and Aristotle defined humans as rational animals. Aristotle distinguished *induction*, the inference of universal principles from particular observations, from *deduction*, in which general principles are used to make predictions in specific situations. Most of what Aristotle had deduced turned out to be incorrect, but his mode of thinking laid a foundation for others to follow. Modern scientists use induction to develop theories and hypotheses, which can then be tested experimentally to arrive at deductions (Fig. 1.1). Greek mathematicians developed the concept of mathematical proof, which allowed the systematic application of logic to deduce a level of knowledge that is regarded as the truth (Box 1.2). Another tradition that arose in ancient Greece was rhetoric, in which oratory was used for the purpose of persuasion. When modern scientists perform experiments and interpret results, they are carrying on the great ancient Greek traditions of reason (*logos*) and persuasion (*rhetor*).

During the so-called Dark Ages in Europe, Islamic scholars helped to preserve and further develop these concepts. Science and mathematics flourished in the Arab world in the Middle Ages (8), building upon earlier intellectual traditions to

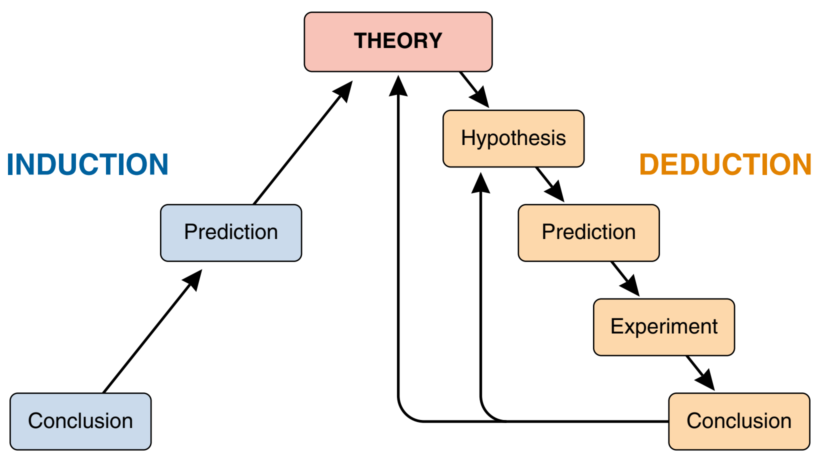

FIGURE 1.1 *Inductive versus deductive reasoning. In inductive reasoning, particular observations are used to infer universal principles or theories. In deductive reasoning, hypotheses lead to predictions that are tested experimentally. The results of experiments in turn may be used to revise hypotheses and theories.*

Box 1.2 Mathematics and science

In 1960, the physicist Eugene Wigner penned an influential essay titled "The Unreasonable Effectiveness of Mathematics in the Natural Sciences" (25), in which he noted how mathematical relationships pervade the natural sciences and, once identified, are predictive of new relationships and findings in nature. The relationship between science and mathematics may be viewed as essential, dependent, intricate, synergistic, and even symbiotic. Science depends on mathematics, and advances in science and technology further the development of mathematics, as evidenced by the ever-increasing reliance of mathematics on computers to probe its secrets, such as finding ever-larger prime numbers. At the heart of the matter is the fundamental question of whether the essence of the natural world is mathematical. The ancient cult of Pythagoras viewed the world as mathematical and promoted its understanding through mathematics, a world view with echoes in Plato's allegory of the cave, in which a perfect world lies just beyond the senses. The ability to express a scientific finding in the precise notation of mathematics is considered an apotheosis in modern science. The increasing recognition that we live in a probabilistic universe has reinforced the notion that both discovered and as yet undiscovered mathematical relationships underlie everything in the natural world, something that Pythagoreans would have embraced and appreciated. Although a detailed treatment of the relationship between mathematics and science is beyond the scope of this book, we encourage budding scientists to learn as much mathematics as they can.

create a body of knowledge that was communicated to Europeans through trade and contacts in the Iberian Peninsula. This eventually blossomed into what is recognizable as modern science during the Scientific Revolution in Western Europe. Two influential publications were Francis Bacon's *Novum Organum*, published in 1620 (9), and Rene Descartes' *Discourse on the Method*, published in 1637 (10). *Novum Organum* proposed an inductive method for understanding natural phenomena in which relevant facts were systematically assembled and categorized according to their association with a phenomenon of interest to generate axioms based on empirical data. *Discourse on the Method* proposed that problems be divided into smaller parts so that the simpler parts might be solved first and urged scientists to begin any inquiry from a skeptical perspective. Scholars continue to debate why the Scientific Revolution occurred in Western Europe rather than elsewhere. Contributing factors include the continuum with classical Greek philosophy, the increasing prominence of academic institutions, the development of printing and the increasing availability of books, a growing crisis between religious and humanistic world views, and the rise of capitalism, which lessened deference to authority and brought scholars and craftsmen together. The result was the emergence of a critical mass of practitioners of the scientific method who gave the revolution an unstoppable momentum (Box 1.3).

Box 1.3 Was science inevitable?

This chapter has emphasized the Western roots of modern science. That the Scientific Revolution occurred in 17th-century Europe in unquestioned, but contributions from many civilizations and cultures made this revolution possible (26). We have already mentioned the critically important contributions of Islamic scholarship. In addition, Chinese civilization developed science-enabling technologies such as the magnetic compass, the printing press, and papermaking, which allowed global exploration and efficient communication. As Bacon recognized, "Printing, gunpowder, and the compass … changed the appearance and state of the world" (9). Chinese astronomy was also highly developed and precisely recorded a supernova in the year 1054, which created the Crab Nebula. It is noteworthy that there is no record of this event in Western records despite what must have been the spectacular event in the night sky, with the appearance of a new, very bright star that was visible during daytime. This curious and mystifying omission from European records may reflect that it conflicted with philosophical-religious consensus at the time, which held that the heavens were eternal and constant. Indian contributions to mathematics, such as the concept of zero, the decimal system, and advanced notation systems, were essential for later advances in theoretical physics (27). In the Americas, the Mayan civilization developed highly advanced astronomy and mathematics, along with the sophisticated engineering expertise to build magnificent cities. Ancient Africans developed advanced astronomy and metallurgy (28). In Oceania, ancient Polynesians mastered navigational skills that allowed them to travel to remote, isolated islands. Hence, the impulse to develop mathematics and science may be seen everywhere that humans settled and built civilizations and reflects the indomitable human curiosity. The will to do science, like the will to make music, can be viewed as a universal human trait. However, in contrast to the development of scientific concepts and mathematics in other

(*Continued*)

Box 1.3 (Continued)

societies, the Scientific Revolution gave rise to unique new insights, formalisms, and ways to investigate the world—the creation of the modern scientific method and scientific disciplines and institutions. The Scientific Revolution allowed humanity to overcome the limits of intuitive thinking, which serves us well in many situations but can lead us astray when trying to understand natural phenomena.

To return to Edgar Zilsel's question at the beginning of this chapter, we must consider the uniqueness of the Scientific Revolution. While there is abundant evidence of curiosity, ingenuity, creativity, and mathematics in many human civilizations, what we call modern science has arisen only once. This alone suggests that science was not an inevitable consequence of the evolution of human thought. Accordingly, science should not be taken for granted. Why it arose in 17th-century Europe, rather than in other scientifically and mathematically sophisticated societies, remains a fascinating and open question. It is probably not a coincidence that Europe during this period also witnessed new technologies like the printing press and telescope, brutal wars of religion, and the upheaval of medieval theology by the Protestant Reformation. Modern science may owe its existence to an unusual confluence of technological, historical, and sociological events.

In the 1920s, a school of philosophy known as *logical positivism*, with centers in the European capitals of Vienna and Berlin, asserted that truth must be demonstrated by direct observation or logical proof. Thus, scientific knowledge was favored over other forms of knowledge. In the classic formulation of the scientific method, science consists of careful observation and description, formulation of a hypothesis, and experimental testing of predictions. An implicit assumption is that experimental results can be replicated by others (chapter 7). Although this so-called "hypothetico-deductive" approach is not the only way of doing science, it is what many people think of when referring to the scientific method.

Logical positivism ultimately fell out of favor among philosophers of science, although its influence on 20th-century philosophy of science is undeniable. One reason for the decline of logical positivism is an inability to provide a clear demarcation between science and nonscience. Any definition of science must be able to distinguish it from pseudoscience, such as astrology, alchemy, creationism, and homeopathy. In fact, separating pseudoscience from science can be difficult since those disciplines have many of the trappings of science, including theory, method, and practice (see chapter 16). For the Austrian philosopher Karl Popper, the issue