SCIENTIFIC METHOD IN PRACTICE

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FOREWORD

Approximately halfway through her Ph.D. program in the biological sciences, my first doctoral student requested that we meet to review progress toward the degree. Knowing that both the research and course work of this student were progressing very nicely, I entered the appointment confident of a glowing report both for graduate student and major professor. However, the discussion took an unanticipated twist as we finished talking about the topics on my agenda.

When and where, this student asked, do we get to the more philosophical part of this Doctorate of Philosophy degree in science? Was it really true that this program that we guidance-committee members had so carefully designed for her was not going to include even one advanced course in philosophy or history of science? If not in formal course work, when would we as major professor and graduate student deal with the logical underpinnings and processes of science at the level of basic principles? The final question had the greatest unintended sting – something to the effect of "Will I graduate feeling worthy of more than a technical degree?"

Stunned and somewhat befuddled, I sent this student on her way with lame explanations: There simply wasn't sufficient time in a modern science education for students to become renaissance scholars as well as well-published researchers capable of competing successfully for federal grant dollars. Moreover, to venture into science philosophy required an unhealthy tolerance for time wasted in silly, perfectionist arguments over whether or not the sun would rise tomorrow. The better path to becoming a successful scientist, I argued, was to function as an apprentice to successful researchers and to get on generating results from real-world experiments. After all, I concluded, the quality of your Ph.D. degree will be at least equal to my own. Had not that Ph.D. landed me a great postdoctoral experience and an enviable tenure-stream Assistant Professor position at a major research-intensive university?

To this day, my former student does not realize how that conversation awakened my conscience to the awesomeness of the responsibility that educators shoulder in passing the scientific torch across intellectual generations. Although it came too late for my first Ph.D. student, that conversation precipitated my sustained appetite for suitable teaching materials to put some Ph. back into the Ph.D. degree in science. For two decades, I have been teaching a graduate seminar course entitled "The Nature and Practice of Science." This course seeks to leaven the minds of College of Natural Science graduate students with sufficient science philosophy, logic, and best practices for enriched and unusually productive careers in science and education. Having found no suitable text for such a course, we have relied on diverse readings, including John Platt, Karl Popper, Thomas Kuhn, Ronald Giere, and others, including university and governmental documents intended for graduate-student science education. Unfortunately, these authors use differing and confusing terminologies, and significant gaps are left that cause instructors and students to struggle in building a unified whole. Moreover, our coverage is introductory; the student or faculty member wishing to seek further is left wondering where to go for more and how to do so efficiently.

Thus it was with enthusiasm and relief that I as a reviewer read this book on *Scientific Method in Practice* by Hugh G. Gauch, Jr. Here at last is a comprehensive and up-to-date treatise on the fundamentals of science philosophy and method between the covers of one book and written from the pragmatic perspective of a credible science practitioner with whom researchers can identify. Here is the book that my graduate student and I needed on the day of our discussion about injecting appropriate Ph. into her Ph.D. degree in science.

The scope and depth of *Scientific Method* are truly amazing. Hugh Gauch has read, distilled, and integrated the contents of literally hundreds of books and articles on science history, philosophy, and practice. Readers treated to the "intellectual gold" emerging from this mammoth "smelting operation" are guaranteed to emerge with a deep sense of appreciation for the efficiency inherent in a well-executed and comprehensive scholarly review yielding a new synthesis. While practicing scientists cannot be expected to read hundreds of texts on science history and philosophy, they certainly can and should read this seminal book.

This is not to say that *Scientific Method* is an easy, comfortable read throughout. Questions of what we humans know, how we can know, with what certainty we can know, and what are the best ways to proceed in efficiently acquiring new knowledge sufficiently reliable to guide practical work and living have absorbed the minds of the greatest thinkers since antiquity. Readers hardly need forewarning that an understanding of a modern philosophical and scientific perspective on these profound questions will require significant work and, in some areas like approaches to statistical analyses, appreciable technicality. However, readers of this book will be rewarded with substantial answers.

Hugh Gauch has done a good job in keeping this important material interesting, sensible, and pragmatic. The book lives up to its billing – it will increase the productivity and perspective of scientists. Thus, in addition to practicing scientific researchers, this book should be of great interest to managers of scientific research. Also, science education has always sought to be grounded in an accurate understanding of science philosophy and practice. So it seems appropriate that science educators should be at the front of the line of folks benefiting from Gauch's work. For that reason, as one involved in science education, I consider it a special honor to participate in the discovery and promotion of this important book.

Finally, it should not be overlooked that *Scientific Method* is a substantial philosophical contribution in its own right. In addition to all of its aforementioned benefits to science practitioners, this book is also Hugh Gauch's attempt to rescue science from the clutches of postmodernist philosophers who argue that the credibility of scientific knowledge is undermined by inherent logical and procedural weaknesses. Science from that weakened perspective becomes nothing special. I find convincing Gauch's rebuttal to the postmodernists and therefore believe that this book makes an important statement to the anti-science political movement currently afoot. Clearly, this book is a major intellectual work establishing and defending a new philosophical position that any mainstream philosopher of science must take seriously.

I boldly predict that in the field of scientific method, the work of Hugh Gauch will stand as a contribution similar in magnitude to the work of a Francis Bacon, Karl Popper, or Thomas Kuhn. Moreover, I would like to think that at the turn of the twenty-first century, this work represents the beginning of a trend away from schism and toward a meaningful reuniting of science practice with philosophy. Each of these major intellectual disciplines has much to offer the other. With the production of this book, Gauch has taken a significant step in recapturing a desirable synergy between science philosophy and science practice, upon which we should capitalize.

Dr. James R. Miller
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East Lansing, Michigan
March 2002

PREFACE

The thesis of this book, as set forth in Chapter 1, is that there exist general principles of scientific method that are applicable to all of the sciences, but excessive specialization often causes scientists to neglect the study of these general principles, even though they undergird science's rationality and greatly influence science's efficiency and productivity. These general methodological principles involve the use of deductive and inductive logic, probability, parsimony, and hypothesis testing. Neither specialized techniques nor general principles can substitute for one another, but rather the winning combination for scientists is mastery of both.

The primary purpose of this book is to help scientists become better scientists, more creative and more productive, by fostering a deeper understanding of the general principles of scientific method. For instance, parsimonious models often can lead to greater accuracy and thereby improve decision-making, accelerate progress, and increase returns on research investments. Also, scientists can improve the statistical analyses of their data by understanding how the Bayesian and frequentist paradigms relate to different research questions and technological objectives.

The secondary purpose is to help scientists gain perspective on science's rationality and role. Every conclusion of science, when fully disclosed, involves components of three kinds: presuppositions, evidence, and logic. Accordingly, an explanation of scientific method amounts to disclosing and securing these three inputs. Also, clearly understood methods beget realistic expectations and legitimate claims. Then scientists can defend science's legitimate claims from influential attacks with a measure of sophistication and confidence, while also perceiving the proper domain and real limits of science, and thereby avoiding excessive claims for science or diminished roles for the humanities. A humanities-rich version of science is more beneficial and engaging than a humanities-poor version.

Understandably, some readers may have greater interest in one of these projects than the other. Those interested in higher productivity should focus on Chapters 5–9. On the other hand, those pursuing philosophical and historical perspective should focus on Chapters 2–4 and 10. Both projects are addressed in Chapters 1 and 12. Science educators will find Chapter 11 particularly relevant. But that said, readers are encouraged not to be overly hasty in judging what is or is not interesting or useful. To master scientific method for the purpose of increasing productivity is commendable, but the ensuing day-to-day labor is arduous and sometimes tedious, so an occasional philosophical joy along the way is not to be despised. On the other hand, to master scientific method for the purpose of gaining perspective on science is commendable, but this turns on understanding scientific practice in technical detail. In a word, this book's two purposes – productivity and perspective – complement each other.

This book's intended audience includes primarily professional scientists and graduate and advanced undergraduate students in the sciences, and it can be used for either individual study or classroom instruction. This book is also for science educators at all levels. Because methods precede results, scientific method is the gateway to all scientific thinking. It is becoming increasingly common for universities to offer courses on the nature and practice of science that are team-taught by scientists and philosophers (and historians, sociologists, and ethicists). Accordingly, some philosophers of science and others in the humanities may be interested to see which topics in their literature are found by scientists to be particularly interesting and helpful.

Because of some unfamiliar historical and philosophical content, at first glance this book may seem somewhat demanding. But in fact, were it added to scientists' bookshelves, it usually would be the least technical book there. Accordingly, although it is more advanced than typical undergraduate texts on science's method and philosophy, motivated juniors and seniors should find it within their grasp.

This book is addressed to a general audience of scientists, rather than being customized for the specific interests of one scientific specialty. To serve those diverse needs, the strategy adopted here is to treat numerous topics fairly thoroughly. Understandably, one reader may be fascinated by the historical contributions of Robert Grosseteste and Albertus Magnus but may be uninterested in the axioms of predicate logic, whereas another reader may have the opposite reaction. Therefore, readers are encouraged to study or skim various sections as their interests dictate, especially when this book is used for individual study.

There are several older books on scientific method that still have much merit, but obviously they cannot address current debates and recent advances (Ritchie 1923; Wilson 1952; Ackoff 1962; Burks 1977; Grinnell 1987).

There is also a more recent book aimed at undergraduates with little or no background in the sciences (Carey 1994). Although admirable for its intended audience and stated objectives, it cannot be expected to benefit professional scientists in their practice. The books by Giere (1984) and Howson and Urbach (1993) are particularly insightful. Other recent books have emphasized historical and philosophical aspects of scientific method (Gower 1997; Rosenberg 2000).

As there did not seem to be a recent book on scientific method aimed at professional scientists and university science majors, this book was written to meet that need. Given the importance of science and technology in contemporary society, and given the inherent beauty and interest of scientific method, it is astonishing that this topic has been so neglected.

Because the literature on scientific method is so underdeveloped, the ideas presented here had to be gleaned from diverse sources far and wide, especially those on the philosophy of science. My role has been largely that of an importer, on behalf of my fellow scientists, gathering useful ideas from numerous books about the history, philosophy, and logic of science. This book is rather different from its sources, however, because there are substantial differences between the needs of philosophers and those of scientists. Philosophers like to study the philosophy of science to become better philosophers, but scientists need to study the philosophy of science to become better scientists. This is a book on scientific method by scientists and for scientists.

Having said what this book is, a few words on what it is not: It is not a systematic or conventional text on the philosophy of science, although it draws substantially from that intriguing literature. Likewise, it is not a comprehensive survey of all topics that might be included in a course on the nature and practice of science, particularly because it does not explore science's ethics and priorities. However, scientific method could well be a core topic occupying a sizable fraction of a more broadly conceived curriculum on the nature and practice of science. Regrettably, this book is not a comprehensive history of scientific method, although a few gems are included. Philosophy, ethics, and history are important, but this book's topic is method, and that poses sufficient challenge.

Finally, in the wars against disease and hunger, as well as poverty and ignorance, scientists and technologists have wonderful opportunities and hence substantial responsibilities. In its larger role alongside others of the liberal arts, science contributes to our picture of the world and life, implying the necessity to capture and communicate a valid picture. The main intention here is to spark a realization that the general principles of scientific method are more difficult and yet more beautiful than some readers may previously have recognized, and thereby to stimulate within the scientific community greater attention to this neglected topic that has tremendous potential to enhance productivity and perspective.

I appreciate helpful suggestions on earlier drafts of various chapters from several scientists, philosophers, and statisticians, including James O. Berger, Mark A. Case, Gary W. Fick, Malcolm R. Forster, William H. Jefferys, James R. Miller, Roger E. Steele, and Martin T. Wells. I am particularly grateful to Gregory J. Velicer, whose wise counsel did much to guide, shape, and encourage this work. Of course, all remaining deficiencies are my sole responsibility. I thank Millard Baublitz, Jr., and P. Andrew Karplus for contributing fascinating case studies to Chapter 9. I also thank James R. Miller for writing the Foreword. I am grateful to my parents, who both were scientists, for instilling in me a love of learning, an interest in science, and a respect for truth. I also appreciate the sustained enthusiasm for this research project shown by my sister and brothers, Susan, Jonathan, Christopher, Gary, and Ken, and their families. Cornell University provided a wonderfully favorable environment for writing this book, especially by virtue of its superb library system.

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Ithaca, New York
March 2002

CHAPTER ONE

INTRODUCTION

This book explores the general principles of scientific method that pervade all of the sciences, focusing on practical aspects. The implicit contrast is with specialized techniques for research that are used in only certain sciences. 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 and implementing effective science education.

The general principles that are this book's topics are shown in greater detail in Figure 1.2. These principles are of three kinds: (1) Some principles are relatively distinctive of science itself. For instance, the ideas about Ockham's hill that are developed in Chapter 8 on parsimony have a distinctively scientific character. If occasionally lawyers or historians happen to use those ideas, they will not be reprimanded. Nevertheless, clearly those ideas are used primarily by scientists and technologists. (2) Other principles are shared broadly among all forms of rational inquiry. For example, deductive logic is squarely in the province of scientists, and it is explored in Chapter 5. 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, such as the principle of noncontradiction. Also, science's presuppositions, which are discussed in Chapter 4, have their roots in common sense. 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.

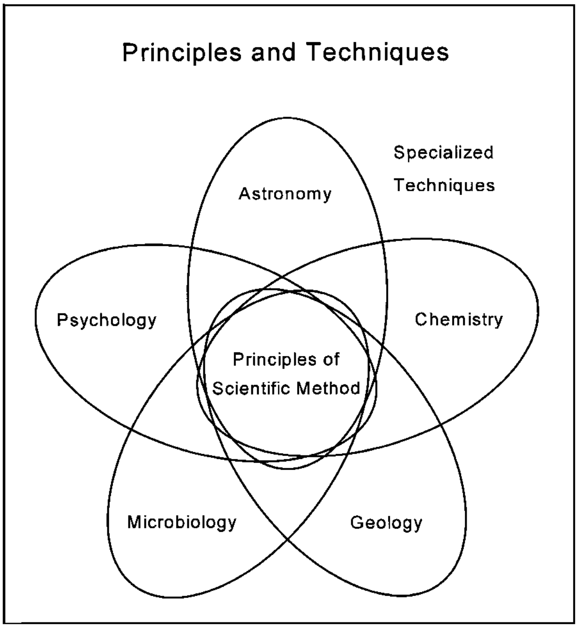

Figure 1.1. Science's methodology depicted for five representative scientific disciplines, which are partly similar and partly dissimilar. Accordingly, scientific methodology has two components. The general principles of scientific method pervade the entire scientific enterprise, whereas specialized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

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. Because there are hundreds of specialties and subspecialties, the overall job of communicating these techniques requires millions of instructional 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 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.

The central thesis of this book is that scientific methodology has two components, the general principles of scientific method and the specialized

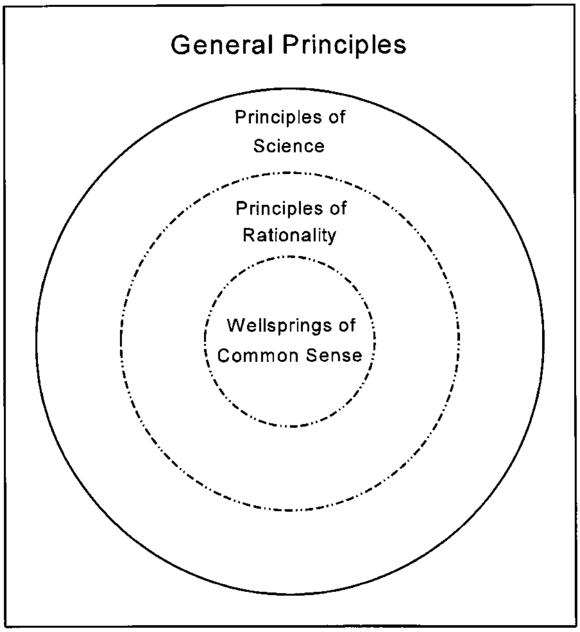

Figure 1.2. Detailed view of the general principles, which are of three kinds: principles that are relatively distinctive of science itself, broader principles found in all forms of rational inquiry, and foundational principles with their wellsprings in common sense.

techniques of a given specialty, and the winning combination for scientists is strength in both. Neither basic principles nor research techniques can substitute for one another. This winning combination can enhance productivity and perspective.

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 here 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 are reliably or impressively truth-conducive. 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 naturally 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 or bother to contribute in a sophisticated and influential manner. But in the humanities, those deep critiques of rationality are currently quite influential. Anyway, by that reckoning, Figure 1.1 should show blank paper.

Moving along to the scientific objection, many 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). In this regard, consider a little thought experiment. Suppose that an astronomer, a microbiologist, and an engineer were each given a grant of $500,000 to purchase research equipment. What would they buy? Obviously they would purchase strikingly different instruments, and each scientist's new treasures would be quite useless to the others (apart from the universal need for computers). By that reckoning, Figure 1.1 should show the methodologies of the individual sciences dispersed, with no area in which they would all overlap.

What of these objections? Is it plausible that, contrary to Figure 1.1, the methodologies of the various disciplines and subdisciplines of science have no overlap, no shared general principles? Asking a few concrete questions should clarify the issues and thereby promote an answer. 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 VISION OF SCIENCE

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 the mainstream opinion.

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), 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).

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, for the topic at hand, the "central premise" of one AAAS (1990:xi) position paper is extremely important, namely, that "Science is one of the liberal arts and . . . science must be taught as one of the liberal arts, which it unquestionably is." 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).

Likewise, 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 science's general principles 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 will occasionally range 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 brief remarks in this and the previous sections are not offered as a rigorous defense of the (controversial) thesis that some general principles are vital components of scientific reasoning. Only a whole book, such as what follows, can aspire to such an ambitious goal. Rather, these preliminary remarks are offered as evidence that the idea that there is a scientific method has enough plausibility and backing to merit careful consideration, not breezy dismissal.

PRIMARY AND SECONDARY BENEFITS

Whatever else may be controversial, one thing that is certain is that mastery of the subject matter proposed and presented here, the principles of scientific method, will require some time and effort. Accordingly, it is natural to ask about the purposes and benefits that will result from this study.

Two general kinds of benefits are expected, namely, increased productivity and enhanced perspective. The primary benefit will be to help scientists become better scientists, more creative and more productive, by providing a deeper understanding of the basic principles of scientific method. A secondary benefit will be to cultivate a humanities-rich version of science, rather than a humanities-poor version, so that scientists can gain perspective on their enterprise.

Regarding the primary benefit, what a scientist or technologist needs in order to function well can be depicted by a resources inventory, as in Figure 1.3. All items in this inventory are needed. 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.

A common concern is that frequently the weakest link in a scientist's inventory is an inadequate understanding of science's principles. This weakness in understanding the scientific method has just as much potential to

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.

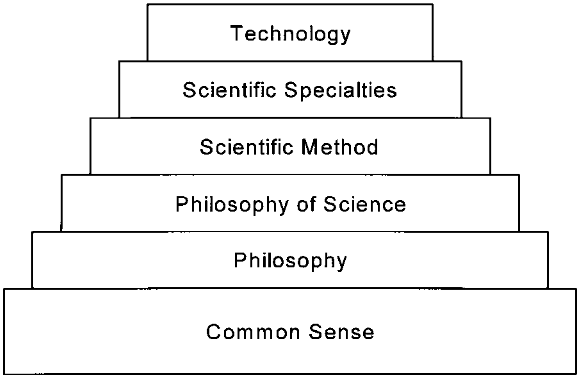

Figure 1.4. Perspective on the place and role of scientific method. The foundations of scientific method are provided by the philosophy of science, which depends more generally on philosophy, which is grounded ultimately by common sense. In turn, scientific method supports scientific specialties and technology.

retard progress as does, say, inappropriate laboratory equipment or inadequate training in some research technique.

Moving along to the secondary benefit, an initial perspective on the place and role of scientific method is offered in Figure 1.4. The scientific specialties and technological accomplishments that emerge from applying the scientific method are obvious. But a humanities-rich version of science will reveal science's roots in the philosophy of science and more generally in philosophy, which is grounded ultimately in common sense. Accordingly, scientific method will be better integrated and more interesting when presented in its philosophical and historical context. Such perspective will also facilitate realistic claims, neither timid nor aggrandized, about science's powers and prospects. A humanities-rich perspective will preclude imperialistic claims about science's domain, with all of the attendant false promises that could only disappoint and alienate.

The topic of science's basic principles has been around for millennia, even before Aristotle (Losee 1993). So naturally many opinions have been expressed about the value of this topic, especially for a scientist's ordinary, practical, day-to-day work. Scientists themselves have written much, as have philosophers, though most of that literature has been rather speculative or anecdotal.

Fortunately, scholars in a different field, the science educators, have done the work of conducting hundreds of careful empirical studies to characterize and quantify the benefits that can result from learning scientific method. Many of those studies have involved impressive sample sizes and carefully controlled experiments to quantify educational outcomes and scientific competencies for students who either have or else have not received instruction in science's general principles. Consequently it has been educators, rather than scientists or philosophers, who have provided the best information on these benefits.

Incidentally, among educators, what here goes under such labels as "scientific method" and "general principles" is most frequently termed the "nature of science." Because Chapter 11 will review the literature in science education, here only brief remarks without documentation will be presented, by way of anticipation. Empirical studies by educators have provided overwhelming evidence for six specific claims.

(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 – somewhat like the way that calcium is better absorbed by the digestive system when accompanied by vitamin D.

(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, and that adaptability will be necessary for productivity as science and technology continue to 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, so including something of science's method, history, and philosophy in the science curriculum results in higher rates of retention of students in the various sciences (and it especially helps those ranked near the bottom, so that educational outcomes can become more nearly equal).

(4) More Realism. An understanding of the scientific method leads to a realistic perspective on science's powers and limits, and more generally to 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, where to look for other scientific work related to their project, and 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, in part because 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. But why? Why does mastery of these principles help scientists to become better scientists? The most plausible explanation is simply that the central 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 specialized techniques of a chosen specialty, and the winning combination for scientists is strength in both. Therefore, adequate understanding of scientific method is essential for an astronomer, botanist, chemist, dietitian, engineer, floriculturalist, geologist, . . . , or zoologist.

BEYOND THE BASICS

Do scientists typically have an adequate understanding of the scientific method? Is it sufficient to yield the expected benefits of productivity and perspective? Unfortunately, the current state of affairs seems rather dismal. "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). Furthermore, countless recent studies by science educators have confirmed that verdict.

The cause of the current situation is no mystery. Scientists are not born already knowing the principles of scientific method, and neither are they taught those principles in a vigorous and systematic manner. "The hapless student is inevitably left to his or her own devices to pick up casually and randomly, from here and there, unorganized bits of the scientific method, as well as bits of *un*scientific methods" (Theocharis and Psimopoulos 1987).

Just where do scientists get what meager bits they do have? Because few science majors ever take a course in scientific method, logic, or the history and philosophy of science, their exposure to any focused attention to science's principles usually is limited to the occasional science textbook that begins with an introductory chapter on scientific method. Figure 1.5 lists typical contents for such chapters.

Despite the perhaps scandalous resemblance of such accounts to the antiquated view of science offered by Francis Bacon in the early 1600s (Urbach 1987; Peltonen 1996), it may well be that elementary ideas along those lines provide the most suitable picture of science to convey to an eighth-grade student working on a science-fair project. Also, it may well be that such a rudimentary cartoon of science is much closer to the mark than is the

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.

currently fashionable postmodern take on science, as reviewed and criticized by Koertge (1998). Whatever its merit in terms of simplicity, such an elementary view of scientific method is wholly inadequate for science professionals and professors. In pursuit of increased productivity and sophisticated perspective, science professionals *must* go beyond the basics.

In some sense, the basic principles of scientific method, or at least their wellsprings in common sense, are obvious and compelling. But these principles are also difficult, challenging, and exacting. They yield their secrets and benefits only to those who pay their dues and do their work. Surely it is sobering to realize in historical perspective that civilizations rose and fell around the globe for millennia before anything recognizable as the scientific method emerged (say around A.D. 1200 to 1600 by various accounts). So there must be some limit to that view about scientific principles being obvious.

Indeed, learning enough about deductive logic to avoid common fallacies is no easy task. Learning enough about inductive logic and statistics to analyze data properly and vigorously is difficult, especially given the internal debate in statistics between the frequentist and Bayesian paradigms. Mastering the principle of parsimony or simplicity in order to gain efficiency and increase productivity is anything but simple, requiring precise distinctions, subtle concepts, and complex calculations. Acquiring some philosophical and historical perspective on science is challenging. And developing the habit of applying general principles to daily scientific work with creativity and effectiveness requires considerable mentoring and practice.

Moreover, these principles work in concert, so to understand their connections and interrelations in a functioning whole, they must be gathered together and presented in a book or in a course in an integrated fashion. Because the principles of concern here are general principles, they do indeed emerge repeatedly in science and technology, but that alone is not sufficient to guarantee that scientists will perceive and grasp their generality. For instance, the case studies in Chapter 9 will reveal parsimony at work in diverse applications in genetics, agriculture, drug design, and electrical engineering. The great risk is that a neophyte may see the material involving parsimony as being just one more of the technicalities needed to accomplish some specialized task. Therefore, it is imperative to present general principles as being truly *general* principles!

If the wide generality and applicability of a principle are taught *explicitly* and *near the beginning* of a scientist's training, then subsequent instances of that principle at work will reinforce the lesson and will promote adaptability and productivity. But if relevant instances involving that principle are merely encountered repeatedly, but with no larger story ever being told, then only the rare student can be expected to assemble the big picture without proper mentoring.

However, despite the deficiencies of the current situation and despite the inherent challenges of this topic of science's principles, two factors are encouraging. They imply that rapid and dramatic improvement certainly is possible:

First, students are receptive, finding this subject matter quite interesting. For example, Albert Einstein observed that "I can say with certainty that the ablest students whom I met as a teacher were deeply interested in the theory of knowledge. I mean by 'ablest students' those who excelled not only in skill but in independence of judgment. They liked to start discussions about the axioms and methods of science" (Frank 1957:xi). Likewise, Machamer (1998) remarked, "Now part of the fun of science, as in most interesting human activities, lies in thinking about how and why it is done, and how it might be done better." Also recall the story about the graduate student in this book's Foreword who eagerly wanted to know "the logical underpinnings and processes of science at the level of basic principles" so that she could graduate with a doctorate in science and feel "worthy of more than a technical degree." Again, countless studies by science educators have shown decisively that students are interested in a humanities-rich account of the principles of scientific method.

Second, the AAAS vision for science includes a vigorous and sustained call for students and scientists to understand these principles well, and it is reasonable to suppose that this leadership will be influential. So, on two counts, there are good prospects for scientists to acquire their winning combination, the principles and techniques that can enhance productivity and perspective. The bottom line is that if this book's central thesis is true, then it will not be possible to keep this winning combination a secret for much longer.

A TIMELY OPPORTUNITY

Again, the central thesis of this book is that science's methodology involves both general principles and specialized techniques, and these principles and techniques together constitute the winning combination for scientists that will enhance their productivity and perspective. However, such views have suffered considerable neglect during the past century or so.

A major cause of that neglect has been the common perception that even if there are such things as the principles of scientific method, the study of those principles would confer no benefit to scientists. For instance, writing in his usual witty and engaging style, Medawar (1969:8, 12) mused, "If the purpose of scientific methodology is to prescribe or expound a system of enquiry or even a code of practice for scientific behavior, then scientists seem to be able to get on very well without it. Most scientists receive no tuition in scientific method, but those who have been instructed perform no better as scientists than those who have not. Of what other branch of learning can it be said that it gives its proficients no advantage; that it need not be taught or, if taught, need not be learned?" (Medawar 1969:8; also see p. 12). In fairness to Medawar, he also remarked that "Of course, the fact that scientists do not consciously practice a formal methodology is very poor evidence that no such methodology exists" (Medawar 1969:9), and he did go on to offer some positive comments.

In any case, the sentiment that scientists get along just fine without probing science's philosophical and methodological foundations is at least common. Such sentiments are mistaken. They bespeak a lamentable and dangerous complacency. Indeed, on three counts, it is time for serious consideration of this book's central thesis.

(1) Science Education. The AAAS has stated with confidence and enthusiasm its vision that a humanities-rich understanding of science makes for better scientists. During the past decade, science educators have generated an enormous literature that provides a wealth of compelling empirical evidence in support of the AAAS vision, as will be reviewed in Chapter 11.

Because this literature is so recent, however, one cannot blame scientists and philosophers in the past for not having taken into account the findings of educators when they offered their anecdotes and speculations about the relevance or irrelevance of science's principles for day-to-day research. But this does mean that earlier assessments, such as that by Medawar, now need to be taken with a grain of salt. More important, any future opinions and reflections from scientists and philosophers about the value of mastering science's principles can gain in realism and interest by incorporating the factual findings of science educators.

(2) Recent Developments. In many respects, the topic of science's general principles is an ancient story with refreshingly enduring content. In some other respects, however, it is a living and growing topic that includes exciting recent developments.

The foremost instance of recent advances is that wonderfully subtle but surprisingly practical application of parsimony, as will be explored in Chapter 8. Briefly, experiments and investigations in many scientific specialties produce large amounts of relatively noisy or inaccurate data. This situation is especially common in some applied sciences, such as agriculture and medicine. Remarkably, parsimonious models of such data can yield findings considerably more accurate than are indicated by the original data. Frequently a parsimonious model can improve accuracy, prompt better decisions, and increase productivity as much as can the collection of several times as much data. Yet the cost of a few seconds of computer time to fit a parsimonious model is minute compared with the cost of collecting much more data, so parsimonious models offer a remarkably cost-effective means to increase productivity.

Sadly, however, that opportunity to increase productivity is one of science's best-kept secrets. Apart from scientists and technologists in a few specialties, such as signal processing, that option is all but unknown. Nor is such an application of parsimony something so simple and obvious that scientists are likely to stumble across it without intentional study and mentoring. The underlying concepts are unfamiliar and even somewhat counterintuitive. Though in typical applications the calculations require only seconds on an ordinary computer, that represents the millions or billions of arithmetic steps in a highly structured algorithm that earlier someone mastered and programmed. Obviously such powerful methods were unknown prior to the general availability of computers beginning in the 1960s, as well as the advent, at around the same time, of some critical developments in statistical theory.

Recent decades and even recent years have seen great advances in deductive logic, probability, and inductive logic (or statistics), as will be explored in Chapters 5–7. So, on many fronts, the recent advances in understanding and implementing science's general principles have been so spectacular that earlier accounts are outdated, and nothing but a contemporary evaluation of the possibilities merits serious consideration.

(3) Appropriate Focus. The AAAS vision of a humanities-rich version of science has breathtaking sweep. The history, philosophy, and methodology of science compose an enormously broad and involved interdisciplinary field.

Consequently, when approaching this field for an audience of science students and professionals, one needs to focus on those specific portions of the information that are of greatest interest and benefit to scientists. Otherwise the result could be more dissipative than beneficial.

Too often the curriculum in science's principles that has reached scientists has been developed along the path of least resistance by borrowing wholesale from the literature in the philosophy of science. But the goal of that literature has been to make philosophers better philosophers, not to make scientists better scientists, and similar remarks could be made about the literature in the history of science or the sociology of science.

Obviously, any book or course for scientists regarding science's principles must seriously engage the companion literatures from historians, philosophers, sociologists, and educators, but the borrowing must be selective and focused if the goal is to help scientists become better scientists. Consequently, any assessment of the value of having scientists study science's basic principles will be inaccurate if that study was based on materials without the proper focus. A scientist could study an enormous number of pages directed at making philosophers better philosophers or making historians better historians and still not become a better scientist. The real issue is whether or not a scientist will benefit from mastering material properly focused for scientists.

There has been little such focus in the past. However, now is the time to put the AAAS vision to the test in a manner that is properly focused and fair. Besides the AAAS (1990) vision, relatively recent position papers that set forth specific recommendations for curricula in the nature of science include those by the AAAS (1989), NAS (1995), NRC (1996, 1999), and NSF (1996). In all of those reports, the principles of scientific method hold a prominent position in the proposed curricula.

So, on three counts, there is now a new day for the thesis that mastering science's general principles can help scientists. The time for complacency is past. The time is right for rapid progress.

PERSONAL EXPERIENCE

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

My research specialty at Cornell University during the past three decades has been the statistical analysis of ecological and agricultural data. A special focus in this work has been agricultural yield trials. Worldwide, billions of

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.)

dollars are spent annually to test various cultivars, fertilizers, insecticides, and so on. For instance, Figure 1.6 shows a soybean yield trial to determine which cultivars perform best. The objective of yield-trial research is, of course, 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 parsimonious model could provide a more accurate picture than could its raw data. So I tried that concept on yield-trial data and found that the resulting gain in accuracy could be assessed empirically and exactly by data splitting using replicated data (Gauch 1988). It worked. The parsimonious model, which required but a few seconds of computer time, typically produced findings as accurate as would have been achieved using averages over replications based on two to five times as much data. Such additional data would have cost tens to hundreds of thousands of dollars, in various instances, so those gains in accuracy and efficiency were spectacularly cost-effective. Furthermore, statistical theory was able to explain that surprising phenomenon, which was demonstrated repeatedly for many crops in diverse locations and agroecosystems.

Accordingly, I submitted a manuscript to a prestigious statistics journal. One reviewer flatly rejected my manuscript, complaining that my results were "magical" and too good to be true – the ideas involving parsimony, one of the principles of scientific method, were just too unfamiliar. But fortunately the editor understood my work better and accepted the paper. Subsequently I published a paper in *American Scientist* that provided a broad philosophical and scientific perspective for understanding the relationship between parsimony and accuracy (Gauch 1993). Meanwhile, the groundbreaking idea (within the agricultural literature) that parsimonious models could increase accuracy and efficiency has now become rather common, and it has made no small contribution to yield increases for many crops in many nations.

The salient feature of that story is that the requisite parsimonious models and computers had been available to agronomists and breeders for a couple of decades, but no one had capitalized on that opportunity until 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. An exact projection is impossible, but a conservative estimate is that parsimonious models of yield-trial data often can support an additional increment of about 0.4% per year (Gauch 1992:184–185).

In other words, for a typical case, if ordinary data analysis supports an average annual yield increase of 1%, whereas a parsimonious model supports 1.4%, then something like 30% of the information in the data is wasted when researchers fail to put parsimony to work. As will be reviewed in Chapter 8, over the past several years there has been compelling evidence from numerous plant-breeding projects that parsimonious models can routinely support that additional yield increment of 0.4% per year.

If an additional increment of 0.4% per year had been achieved after that window of opportunity was opened around 1970, then today's crop yields would be 12.7% higher. But to be conservative, suppose that just half of that advantage had been transferrable from research plots to farmers' fields. Even then, putting parsimony to work could have increased crop yields by 6% over the past 30 years. That may not seem like much, but given that the world's population today is about 6 billion people, that 6% increase would feed 360 million people, more than the population of North America.

But tragically, that window of opportunity from 1970 to 2000 has come and gone. Thus far, only a fraction of agricultural researchers have learned to use parsimonious models to gain accuracy, and even that limited application did not take place until the last of those three decades. The resultant loss of 6% is now irretrievable, because breeding is an incremental process. Each year's efforts begin where the last year left off as breeding stocks are gradually improved. Even though parsimony can be put to work in greater measure in the future, that does not change the historical fact that the ongoing process of plant breeding already has built into it a 6% opportunity cost, caused by neglecting parsimony from 1970 to 2000, and that loss can never be erased. Opportunities come and go; they do not linger forever.

What was missing? What caused that now permanent 6% reduction in crop productivity? It was not the lack of specialized techniques. Nor was it inability to easily perform billions of arithmetic steps. Nor was it lack of funding. It was lack of understanding, or, better yet, mastery, of parsimony, one of the principles of scientific method. What was missing was the last of the critical resources listed in Figure 1.3.

Needless to say, during the past three decades, countless additional measures could have been taken to strengthen agricultural research and thereby to boost farm productivity. The lost 6% could have been regained in many different ways. What is so remarkable about that particular lost opportunity to exercise parsimony, however, is how cost-effective it would have been. Besides having low cost, it also would have involved low risk, because that approach to data analysis had already been tried and proved, unlike many other possible measures that were unproved and risky. Nor would any new or different or expensive requirements have been imposed on data-collection procedures. Rather, the missed opportunity was failure to apply parsimonious models to extract more accurate and more useful information from data already in hand using computers already in place.

That loss is analogous to buying a bag of oranges and then squeezing out only half of the juice. Such waste doesn't make sense. Regardless of which particular opportunities could have been used to change agricultural research for the better, one factor remains the same: Whatever data are obtained, it makes sense to extract all or nearly all of the useful information from the data. Getting only half of the juice is deplorable. And the only way to get all or nearly all of the juice is to master not only research techniques but also general principles.

The bottom line is that for lack of mastering the principles of scientific method, crop yields worldwide are now considerably less (about 6% less) than they could have been had the value of parsimony been appreciated three decades earlier. The principles of scientific method matter.

The larger issue that this example 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, be it parsimony or another principle in a given instance. Precisely because these are *general* principles, my suspicion is that my own experience is representative of what can be encountered in countless specialties, as the diverse case studies in Chapter 9 will clearly indicate.

Finally, these reflections on my own experience have focused thus far on only one of the two proposed benefits, namely, productivity. On balance, something might be added about the other benefit, namely, the perspective gained from a humanities-rich perception of science. My own experience resonates with the AAAS (1990:xi) expectation that broad experience of science as a liberal art is worthwhile for "the sheer pleasure and intellectual satisfaction of understanding science."

Like the graduate student mentioned in this book's Foreword, I also had a restless curiosity and deep interest regarding the basic principles of scientific thinking. And also like her, that spark of curiosity had received no stimulus or encouragement whatsoever from the courses and ideas presented in my university education. Nevertheless, such curiosity is normal and common, as Aristotle observed in the opening words of his *Metaphysics*: "All men by nature desire to know" (McKeon 1941:689). More recently, the AAAS (1990:xi) has reaffirmed Aristotle's observation that there is great satisfaction and pleasure in "the human desire to know and understand."

In a campus bookstore, I stumbled across a book by Burks (1977) not long after it was first published in 1963. Arthur Burks was a professor of both philosophy and computer science. His book was quite long, about 700 pages, and frequently was rather repetitious and tedious. But 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 continuing interest in the principles of scientific method, most notably that by Jeffreys (1983), which was first published in 1961.

Thus my interest in science's principles dates to about 1965. For the next two decades, my primary motivation for that interest was – to echo the AAAS – the "sheer pleasure" that accompanies "the human desire to know and understand." Grasping the big ideas that are woven throughout the fabric of the entire scientific enterprise generates delight and confidence.

Because of youth and bad company, however, the idea that mastery of those principles could also promote productivity was an idea that would slumber in my mind for a couple of decades! It was not until 1982 that some scattered thoughts began to be reawakened and to coalesce (Gauch 1982), eventually resulting in the *Biometrics* article mentioned earlier (Gauch 1988). Since then, I have been keenly aware that the principles of scientific method can enhance not only perspective but also productivity. Whether at present my interest in these principles is motivated more by a desire for intellectual perspective or for scientific productivity I am not able to say.

SUMMARY

This book takes as its subject matter the general principles of scientific method that pervade all of the sciences, as contrasted with specialized techniques that occur only in some sciences. These basic principles include hypothesis generation and testing, deductive and inductive logic, parsimony, and science's presuppositions, domain, and limits.

The primary benefit to be expected from understanding these principles is increased productivity. A secondary benefit will be a humanities-rich version of science that will promote a wider perspective on the scientific enterprise. To obtain these benefits, however, scientists must go beyond the basics of scientific method. They must master the principles of scientific method as an integrated, functioning whole.

The central thesis of this book is that scientific methodology has two components, the general principles of scientific method and the specialized techniques of a chosen specialty, and the winning combination for scientists is strength in both. Neither basic principles nor research techniques can substitute for one another. This winning combination will enhance both productivity and perspective.

On three 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 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. Third, my own research experience, primarily involving agricultural yield-trial experiments, confirms the two expected benefits. Mastery of the principles of scientific method promotes vital scientific productivity and technological progress. In addition, there is intellectual pleasure in gaining a humanities-rich perspective on how scientific thinking works.