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Introduction

Science is a primary force driving societal development. Science exists as a consequence of human curiosity about the natural world and of the practical needs of civilizations to survive and prosper. Knowledge (in Latin, "scientia") is what provided the means to manufacture the paper on which these words were printed, to fabricate the printing presses that did the imprinting, to extract the dyes that formed the letters, and to build the engines of the trucks that delivered the book to the bookstore. Science produced the medical knowledge necessary to prevent or cure illnesses that used to kill so many as infants or children. It enabled us to travel to the moon, explore distant planets, and study galaxies. Let's also not forget that without science there would be no Internet and no social media (whether this actually has been more of a benefit than a nuisance remains debatable).

Science is one of the few endeavors that provides those with insatiable curiosity a never-ending source of questions and answers. Curiosity may, in fact, be what all scientists have in common and the reason they became scientists. Scientists do want to discover new things about the natural world, things that will help humans exist in, and manipulate, the world to their advantage. However, most are committed to science for its own sake. To understand this better, let us consider young children asking the question "why?" This question is a natural expression of the curiosity of the child and a product of the evolutionary value of education for species survival. Parents, and others, often perceive the question as "cute." However, when the question is repeated incessantly, that cuteness can turn to annoyance. For the successful scientist, however, the "why" question initiates the search for greater understanding of our world. It drives the scientist to look deeper into questions and to search for ever greater elucidation of natural phenomena. With each new insight obtained, many other questions emerge. In short, scientists never are able to satisfy their desire to know why, which is not an annoyance, but a wonderful, challenging, fulfilling, and important endeavor that brings the great joy. Stuart Firestein put it this way:[1]

> I am afraid that it is impossible to convey completely the excitement of discovery, of seeing the result of an experiment and knowing that you know something new, something fundamental, and that for this moment at least, only you, in the entire world, knows it.

[1] Quotation from Firestein [3], p. 160.

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In a *Science* article published in 2017 [4], scientists offered their opinions about why science is important to them. These scientists were from diverse fields and emphasized the importance of science for, among other things, sustainability and conservation, human health, truth, shared history, shared future, and discovery and wonder. Samantha VanWees offered a particularly personal and insightful comment about the question "why?"

> Thanks to public education and television, I fell in love with science and research at a young age. I've studied why bread rises, why meat browns, why canned peas soften, and why food tastes so darn bad on airplanes. We like to think of science as facts and logic, but really science is about finding out just how much we don't know. We must continue investing in science so children know the importance of asking "why?" Science and wonder are all around us, all the time. You just have to look for it.

One may gain satisfaction in knowing why and then moving on. The question has been asked and answered. "I have learned the answer and thus I am more knowledgeable." However, each quantum of knowledge raises more questions than it answers. In this way, the scientist, over years and decades, may increasingly appreciate the surprising breadth of ignorance they exhibit. In essence, and paradoxically, the more one knows the more one realizes how ignorant they are. This may, at first, appear unfortunate. I argue that it is not. Instead, it is a reflection of the success of the effort to reveal the truths of the physical world, and in doing so, simultaneously reveal the world's complexity. It should be a humbling experience, and this is critically important for reminding the scientist of how difficult and tenuous the search for truth is. Darren Saunders, University of New South Wales,[2] expressed this notion quite nicely when he said:

> So many questions without answers. So many experts with differing views. A brutal realisation that things don't work the way we always thought. Seeing infinite shades of grey instead of that comforting black and white world. Sound familiar? Welcome to the mind of a scientist.

Science is a field of endeavor that is endlessly fascinating, stimulating, and enriching. Science also can be incredibly difficult, frustrating, and exhausting. I have loved science since the time, as a child, that I first visited my parents' clinical laboratory. Hearing the whining of centrifuges, seeing donut-shaped, pink erythrocytes and purple and white polymorphonuclear leukocytes in a microscope, or looking at clear solutions in a water bath suddenly become turbid, were magical experiences. For the next half-century, from public school to the university to graduate school to postdoctoral fellowships and through the professorial ranks, science has remained a love. In fact, doing science has been and remains more of an avocation than a vocation. Most scientists feel very lucky to be "doing science" rather than having a "real job."

What does it mean to "do science?" Doing science is not a job at which you punch the clock when you arrive and when you depart. It is not a compartmentalized component of your existence. Science can be, and often is, a way of life. In this sense, it has stages much like birth, childhood, adolescence, adulthood, old age, and death. Doing science requires parenting (mentoring), schooling, learning to function in a community, developing a sense

[2] See "Uncertain? Many questions but no clear answers? Welcome to the mind of a scientist." https://theconversation.com/uncertain-many-questions-but-no-clear-answers-welcome-to-the-mind-of-a-scientist-134388

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Table 1.1 *What if? This table uses the well-known fishing metaphor to illustrate, in science education and beyond, the value of integrating the history and philosophy of science with the practice of science.*

If you give a person a fish	→	they can have *a* meal
If you teach a person how to fish	→	they can have *many* meals
If you provide a context for fishing	→	they can find out *why* one would fish in the first place, evaluate the desirability of fishing, learn about successful and unsuccessful fishing methods utilized from antiquity to the present, determine if fishing might be damaging to the environment, decide if one was or was not concerned about such damage and why or why not, appreciate the potential emotional rewards or frustrations of the activity, consider whether teaching one's progeny how to fish would be desirable, develop awareness of other methods of food acquisition, evaluate the moral question of whether one should kill and consume fish, etc.

of one's own individuality, making mistakes and overcoming them, establishing one's own niche in the scientific world, and finally, raising your own scientific children.

The *gestalt* of the scientific enterprise is rarely, if ever, considered explicitly in science education. Yet this consideration is critical if new generations of scientists are to acquire a holistic perspective of their own field. A holistic treatment of the scientific enterprise provides the practical and philosophical knowledge to enable a person to appreciate and to "do" science better. This is not a goal relevant only to a small community of cloistered practitioners of the philosophy of science. If societies are to thrive and evolve, it is incumbent upon them to produce the most capable scientists.

In much the same way as strategic planning is a prerequisite and a foundation for the execution of tactics that will achieve a desired outcome, an appreciation of the *gestalt* of science is a prerequisite for optimal experimental planning and execution. In short, to be a successful scientist, one must know substantially more than a series of useful facts like Avogadro's number, Michaelis-Menten kinetics, electron orbital geometry, or nucleosome structure. It is not enough to be a bright, energetic, objective participant in paradigmatic science. One must dig deeper and look more broadly,[3] especially into the historical and philosophical principles providing the foundation for science practice. Table 1.1 provides a conceptual illustration of the value of this approach. Table 1.2 lists achievements fostered by the integration of science history, philosophy, and practice.

The thesis of this volume is that if one is to "do science" most effectively, and to derive maximal satisfaction from the endeavor, one cannot simply execute the technical processes

[3] It is interesting that the terminal degree in science is a Ph.D., which designates one as a *Doctor of Philosophy*, yet it is rare that graduate programs have any requirements for education in philosophy itself. This has led some to question whether the scientific Ph.D. represent anything more than a technical degree (see foreword by Miller in Gauch [5]).

Table 1.2 *Why integrate science history, philosophy, and practice?*

To understand the philosophical and historical reasons science is done as it is	To understand and use the scientific method
To create a foundation for truth	To find truth
To create a scientific experiment or project	To appreciate the loveliness of nature
To formulate a hypothesis	To evaluate hypotheses
To understand	To explain
To improve analytical and theoretical thinking	To justify public policy decisions
To apply logic in inferential processes	To insure assumptions are reasonable
To explore assumptions intrinsic to knowledge creation	To integrate probabilism into hypothesis creation
To understand different methods of knowledge creation	To understand the limits of your understanding
To chart new directions for science	To solve intractable problems
To enjoy thinking deeply	To know "why"

that comprise experimental science – *one must "understand" science*. A person who is expert at such processes certainly is a gifted technician, and science cannot be accomplished without such expertise, but a scientist is more than a person *doing* experiments. The scientist is a thinker, not just *in addition* to manipulating scientific instruments and materials, but first and foremost. Chemical robots that perform high throughput chemical reactions are superb at this task, but they are not scientists in the classical sense.

As with any book on a particular subject, one generally starts by defining it. Chapter 2, "Defining Science," considers this question. It turns out that it is difficult, if not impossible, to reach consensus on what science is, but the attempt to do so introduces the reader to a general theme of this book, when one "digs deep," one may be surprised that their knowledge base is not as firm as they thought, if at all. One has had the rug pulled out from under them.[4] Digging deeply and holistically is one approach for minimizing, but not eliminating, this risk.

If one can't define science, then distinguishing it from nonscience also appears hopeless, yet this distinction has become critical in this political, internet age. With the ability to disseminate information with single key click, we are now experiencing not just an "information age," one in which the amount of credible, logically supportable, fact-based information has exploded, but an age in which, as in Orwell's book *1984*, language has been transmogrified into Newspeak, which facilitates and encourages contradictory expressions such as "War is peace," "freedom is slavery," and "ignorance is strength." In 2022, we have

[4] I can think of no better vignette for this metaphor than the following. "The rabbinical student is about to leave for America. When he asks his mentor for advice, the rabbi offers an adage that, he tells the student, will guide him for the rest of his life. 'Always remember,' the rabbi said sagely, 'life is like a fountain.' Deeply impressed by his teacher's wisdom, the student departs for a successful career in America. Thirty years later, he learns that the rabbi is dying, so he returns for a final visit. 'Rabbi,' he says, 'I have one question. For 30 years, whenever I was sad or confused, I thought about the phrase you passed on to me, and it has helped me through many difficult times. But to be perfectly frank, I have never understood the full meaning of it. Now that you are about to enter the realm of truth, tell me, dear rabbi, why is life like a fountain?' Wearily, the old man replied, 'All right, so it's not like a fountain.'"

shrill statements such as *"the truth of science is false."* What are we to believe, and why? These questions are among those addressed in Chapter 1.

Chapter 3, "Learning Science," focuses on concepts of science outside the purview of rote learning, concepts that are more metaphysical and sociological in nature. I discuss how history has shown that facts may be fallacies and fallacies may be facts ... depending on historical context. I then discuss how personalities, not just scientific knowledge, can drive science forward. Personality traits such as courage, unwavering commitment, immunity to criticism, farsightedness, intuition, perspective, and yes, egotism, all are associated with great leaps in science, from before Galileo and on to Isaac Newton and Gottfied Leibniz, Niels Bohr and Albert Einstein, Max Delbrück and Seymour Benzer, and more recently, Stanley Prusiner.

One would think that knowledge drives science forward, but one would not be entirely correct. It is not knowledge *per se*, but rather ignorance, that drives scientific advancement. If one *already* knows something, i.e., one possesses knowledge, there would be no reason to search for more – unless this knowledge raised questions or issues about which one was ignorant. It is the recognition of ignorance that propels us forward. "I don't know how this works. Let's create a hypothesis why and then test it experimentally to see if it explains." What happens, however, if we don't know what we don't know? How are we to reveal questions about a universe that exists in all its complexity without knowing the questions that could be asked? In Chapter 3, we discuss this and learn how to be *more* ignorant.

When we "create a hypothesis why, and test it experimentally," it is highly likely we will do so using the "scientific method." It may seem to some that this method is a product of modern science, but surprisingly, elements of it can be found in antiquity, in Egypt 5,000 years ago, and in the writings of Aristotle in the fourth century BC. How the current scientific method came into being is the subject of Chapter 4, "Development of the Scientific Method: From Papyrus to Petaflops." Here, I trace what I believe are the key moments and key people that contributed significantly to this process. I move from the time of Ptolemy to the great leaps made in the Islamic world during the tenth and eleventh centuries, to the scientific revolution of the sixteenth and seventeenth centuries, and on to what I call the "probabilification" of the method in the early twentieth century. The scientific method has been the mainstay of science throughout history, but does it remain so in the twenty-first century? Some think not, arguing that there *is* no scientific method or "anything goes," and with the development of powerful computers and algorithms, a new scientific method, "data-driven science," may signal the end of the scientific method as we have known it.

Putting aside this eventuality for the moment, Chapter 5, "Science in Practice," discusses the process of science, including how scientists choose projects, experiment, observe and interpret, and infer. Inference has always been the bread and butter of science. We see something happening consistently, and we generalize this observation into a law, a hypothesis, or a theory. We do this through abduction, induction, and deduction, three modes of inference. But how does one actually conceive of a theory or select one from among many candidates? Once determined, how does one know that their theory holds water? How are theories tested? These are among the issues discussed.

When one develops a theory, one does so believing it is a true reflection of processes occurring in the natural world. Is this belief warranted? *Does* science actually explain the real world or does it just explain a world we imagine? This question is at the center of debate among those who answer "yes" (realists) and those who answer "no" (anti-realists). But wait, what do people mean when they use the term "realism?" Maybe in one context our theories *are* real, but in others they are not. Could our sense of realism be somewhere between the poles? Maybe realism is neither solely empirical nor theoretical, i.e., maybe it is metaphysical in nature. Even if we *are* realists, does knowledge = understanding?

Knowledge has been characterized as "justified true belief," which in many cases comes through statistics. Statistics is an obligatory part of training in science because it gives us the tools to determine if our observations are or are not "significant," i.e., whether we are justified in believing them. Significance in this context usually means $p < 0.05$, which is a value almost universally accepted in the biomedical sciences.[5] But why? As we dig a little deeper into the question, we find that the convention of considering an observation with a $p < 0.05$ significant was *arbitrary*. One could just as well have chosen $p < 0.01$ or $p < 0.001$. What is more disturbing is how confidence intervals are (mis)used and so lead us to make unjustified conclusions. This is a particularly large problem in clinical trials and one that is responsible, to a significant degree, for their low replicability (10%!?). All of these issues beg the question of "how do we know something is true?" a question addressed in the last section of Chapter 5.

We have discussed practical, theoretical, historical, and philosophical aspects of science. Each can be said to comprise elements with certain levels of predictability. For example, we have the practical skills necessary to determine the melting and boiling points of chemicals, which are constants. We construct theories guided by logic, laws of nature, and observations of our own or of those of others. We consult the written historical record to understand the genesis of our world and the things in it, a record we can always come back to knowing its elements will remain relatively constant.[6] We use the tools of logic to frame philosophical arguments. The *ways* we go about doing these things, although not rigidly codified, do lead to the expectation that two people ostensibly doing the same thing will produce the same result. However, as they say in cheesy[7] commercials for useless gimmicks on day-time television in the United States (all for $19.95 [shipping not included]), "But wait! There's more!" The "more" is illogic, irrationality, impulsiveness, dogmatism, competitiveness, the quest for fame, hubris, career advancement, political or commercial agendas, etc. – in a word, "sociology." Few may appreciate the importance and impact of sociology on science practice. It is immense and unpredictable and is considered in Chapter 6, "Science as a Social Endeavor." The Gershwin song, "Let's call the whole thing off," provides a lyrical example of the unpredictability of human (including scientist) behavior.

[5] The *p*-value is the likelihood a given experimental result is due to chance.

[6] Divergent historical reports may exist and interpretations of those reports may differ, but the root literature remains constant even as new information is added. We don't rewrite Newton's *Principia* or purge the historical record of things we don't like (unless we live in totalitarian societies in which the government determines to what information people will have access and the level of veracity of that information).

[7] For those not familiar with this expression, definitions include "bad quality or in poor taste, tacky, tasteless."

You say eether and I say eyether
You say neether and I say nyther
Eether, eyether, neether, nyther
    Let's call the whole thing off!
You like potato and I like potahto
You like tomato and I like tomahto
Potato, potahto, tomato, tomahto!
    Let's call the whole thing off!