Introduction

THE IMPORTANCE OF DEFINING SCIENCE

The terms "science" and "scientific" have come to have a special meaning and to carry a special weight in modern society. Professional scientists tell us that genetically modified foods are safe to eat, that industrial emissions are causing global warming, that vaccines don't cause autism, and that some medications are safe and effective while others are not. A consumer product seems more trustworthy if it's described as "scientifically proven" or if "clinical studies have demonstrated its effectiveness." Politicians and lobbyists often evoke "scientific proof" in arguing for certain positions or policies. Our federal government invests taxpayer dollars in "scientific research" of different varieties. Whether something can be categorized as "science" determines if we allow it to be taught in our public school science curricula, as in the ongoing debate over teaching evolution vs. intelligent design theory.

To evoke "scientific" in the description of a claim makes it seem different, and likely more credible, than claims of a nonscientific nature. Rarely, if ever, do we read of a healthcare product being "philosophically proven to heal" or "theologically demonstrated to cure." But why does the label "scientific" carry any special weight at all? What does it mean when we say that something is "a scientific fact"? Doesn't science sometimes get things wrong, and if so, why should we believe future scientific claims when past claims have sometimes been in error? Even if we stipulate that science does and should carry special weight, how are we to know if something really is scientific? How much trust should we put in the claims that scientists make, and how are we to evaluate whether the claims themselves

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really are based on science? Overall, the question becomes: What does it mean to be scientific, and how can we define science?

Scientific and technological progress has transformed how humans live in countless ways. For this reason, science's ability to predict and manipulate the natural world certainly appears to imbue scientific knowledge with at least a greater degree of practical utility than other forms of knowledge, if not a greater degree of truth. Most people seem to accept that science is different in some way, and if such is the case, it seems as though we should be able to define what science is and how it is different from that which is not science.

As for myself, I come to this problem as an academic professional physician and scientist who pursues both independent research and is deeply involved in the teaching of students of science at the graduate level. The formal education of scientists focuses almost exclusively on the doing of science, not the understanding of what science is. Most doctoral students who are in advanced educational programs designed to train the next generation of scientists spend their time observing mentors and fellow students and, initially, learning through imitation and repetition. Formal coursework is provided in order to instruct students in the current beliefs and cutting-edge theories of their chosen field and the accepted evidence that supports (or refutes) such theories; however, little if any classroom instruction is typically given regarding the *process* by which science is done. Rather, this is learned by doing and by observing the doings of others (fellow students, technicians, postdoctoral fellows, and faculty mentors), over and over again. Eventually, one may begin to see patterns in how the field functions. One often begins to think about the process of the scientific approach itself. One analyzes *how* humans study nature, the strengths and weaknesses of different approaches, and the pitfalls to be avoided. However, in this latter task, it is ironic that while scientists themselves are the leaders in the practice of science – the ones who know "how to do the thing" – they are amateurs in the formal analysis of what science is.

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There are whole academic fields (separate from the practice of science itself) that focus precisely on how scientists study nature; in particular, the philosophy, history, psychology, anthropology, and sociology of science, as well as integrated studies that combine these different areas to give a broader view. Whereas my fellow scientists and I study nature, these fields study us. Sadly, in my experience, practicing scientists are seldom very much aware of the details of such fields and in many cases may not know that such fields even exist, other than having heard rumors to that effect. This is not to say that scientists aren't very good at practicing science; theoretical knowledge of the inner workings of an internal combustion engine and the ability to drive a car are separate areas of understanding, and one can be an expert in one while being entirely ignorant of the other. Many scientists can recognize good science when they see it and can call out flawed science when it is encountered, or at least they believe they can, as this is the basis for the entire peer-review system in science. However, because they can judge science does not necessarily mean they can clearly articulate the theoretical underpinnings of what defines science, of how science works and/or how science fails.

If even professional scientists are not typically trained in the general underpinnings of scientific knowledge claims, how is there any hope for nonscientists to understand what level of confidence they should (or should not) place in science and the claims it makes. Moreover, how can people be expected to distinguish valid scientific claims from all manner of flim-flam and fluff? The goal of this work is to help lay people, students of science, and professional scientists understand and explain how science works in general, the strengths and weaknesses of scientific thinking, and the extents and limits of scientific knowledge claims.

Despite the weight that the label of science may carry with many people, it is an utter fiction that there is (or ever has been) a uniform consensus among scientists (or anyone else for that matter) as to what precisely defines science. This question has been tackled over the years by many great scholars and yet there is not a clear and

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unequivocal answer. Nevertheless, much progress has been made, and this has generated a greater understanding of characteristics of science, its practice, and its strengths and limitations. The goal of this work is to communicate a broad view of that progress. This is an ambitious goal to be sure, but the difficulty of the task does not diminish its importance. What has been learned is surprising, counterintuitive, and complex. Ultimately, it speaks not only to science but to the human condition itself.

GOALS AND ORGANIZATION OF THIS WORK

When I introduce the reader to concepts generated by the outside fields that study science itself, I am reflecting the insights, innovations, and contributions of others – standing on the shoulders of giants. I name the giants when I can and have taken care to try and point out to the reader what the original source of many concepts are and what resources and further reading one might do to explore the more granular details of different specialized areas of focus. However, the richness of these different fields goes so deep, that much will be neglected – other works devoted to the finer nuances and details of each component field are abundant, and one need only seek them out. Herein I attempt to synthesize key ideas into a unified framework, hopefully making it coherent to the reader. In addition to explaining the progress of those who study science, I contribute the perspective of the thing being studied – a view of great utility. I speak with the voice of the bacterium on the observations, interpretations, and theories of the microbiologist, for I believe that I know what it is to grow in the chaotic ferment of the microbial culture.

The book is organized into three parts. In Part I (Chapters 1–3), the individual working parts of scientific reasoning and logic are described (and then an attempt is made to draw a picture of scientific reasoning as a whole). In Part II (Chapters 4–8), flaws that undermine natural human observation, perception, and reasoning will be described. In Part III (Chapters 9–13), I will explore how scientific processes and methods try to address these flaws, attempting a

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distinction between scientific and nonscientific thinking. An overarching theme of the final part of the book is how science mitigates the tendencies of normal human thinking to "get the world wrong" in particular situations.

The first goal of this book is to help guide nonscientists in having reasonable expectations of what science can and can't do. Scientific claims are often regarded with either too much confidence or too much skepticism by different groups of the general public. This book strives to lay the groundwork for a healthy balance in how to weigh scientific knowledge claims. The second goal of this book is to help professional scientists gain a better understanding and codification of the strengths and weaknesses of their craft and the role they play in portraying it. Of high importance to this latter audience is the recognition that it is quite intoxicating, from an ego standpoint, for scientists to be regarded as the arbiters of "true" knowledge. This has been described as "the Legend" of science.[1]

The extreme version of the Legend claims that "science aims at discovering the truth, the whole truth, and nothing but the truth about the world" – a less grandiose version of the Legend states that science is "directed at discovering truth about those aspects of nature that impinge most directly upon us, those that we can observe (and, perhaps, hope to control)." While it is argued that the Legend has been abandoned by those who study science, the Legend (or a slightly weakened version of it) seems very much alive among some in the lay public. In my experience, scientists themselves hold onto a version of the Legend, and while it is less extreme than a philosophical truth, it nevertheless has some component of being "truer" than that which is not science. In my view, scientists should neither seek nor accept the extreme versions of the Legend, which are pleasant in the short term but harmful in the long term, and ultimately destructive as they lead to unsupportable claims. Failures to live up to hyperbolic

[1] Kitcher P. 1995. *The Advancement of Science: Science Without Legend, Objectivity Without Illusions*. New York: Oxford University Press.

attributes only leads to anti-Legend, those who claim with vitriolic hostility that science is, at best, nothing at all, and at worst, a grand conspiracy to dupe the world. Rather, we must seek a balanced and honest view based on realistic assessments. Science's greatest apparent weaknesses are, in actuality, its greatest strengths; as professional scientists we should embrace this and not seek to minimize or ignore it. In the greatest traditions of scientific scholarship, let the existing data of what science is inform us as to the properties of science itself – let us look it in the eye, unflinching, and without spin or propagandist inclinations.

A RIDICULOUSLY BRIEF HISTORY OF SCIENCE VS. NONSCIENCE

Early on (dating back to antiquity) and arguably from a position of great overconfidence, scholars of science often stated that science (or natural philosophy as it was called before the 1830s) dealt with facts, whereas other schools of thought dealt with opinions. However, as many established scientific facts were later rejected by subsequent generations, they came to be understood as fallible and thus not so different from opinions.[2] Yet the realization that scientific facts are imperfect doesn't mean that they don't have a different character than nonscientific knowledge claims. But if they do (which is not a given), why is that so, and what is the justification for such a view? Later thinkers gravitated to the notion that if it is not fact that distinguishes science from other ways of knowing, then it must be the manner by which scientific claims are generated and/or evaluated that distinguishes science from nonscience. In other words, the method that science uses to create knowledge has a special character that is different from nonscientific approaches.

[2] Laudan L. 1983. "The Demise of the Demarcation Problem." In Cohen RS, Laudan L (Eds.). *Physics, Philosophy and Psychoanalysis: Essays in Honor of Adolf Grunbaum*. pp. 111–27. Dordrecht: D. Reidel.

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For the reasons just stated, most modern attempts at defining science have focused on *methods* or *modes of thinking* that distinguish scientific activities from nonscientific activities rather than the specific content of scientific knowledge claims. However, while one often encounters discussions of "the scientific method" and its application to investigation, there is a lack of agreement about what precisely this method entails, and there are those who argue that the very notion of a scientific method is itself an utter myth.[3] It has further been argued that different areas of scientific study favor different types of method(s), and thus one cannot precisely define "science" or "the scientific method" per se.

Moreover, it has been argued that even if some broader characteristics can help identify a method as scientific, precisely demarcating how science differs from other ways of thinking is neither possible nor useful.[4] It has even been claimed that science flourishes only with a distinct lack of required methodology, and that attempts to codify a scientific process will only serve to destroy it – in other words, the only rule of science is that "anything goes."[5] However, this latter view is somewhat radical and is certainly not embraced by most professional scientists, as evidenced by certain generally agreed-upon standards used in the practice of peer review of reports of scientific discoveries, grant applications, and research.

Scholars of science have often rejected any definition that would render the great historical scientists as "nonscientific." While this seems logical, it presupposes that those who have made the most progress and achieved the most recognition were those acting most scientifically – a question we shall explore in detail. Perhaps more importantly, it assumes that the scientific method, however we define it, has been stable over time, a claim that seems hard to justify.

[3] Bauer HH. 1992. *Scientific Literacy and the Myth of the Scientific Method*. Urbana and Chicago: University of Illinois Press.

[4] Laudan L. 1983.

[5] Feyerabend P. 1975. *Against Method: Outline of an Anarchist Theory of Knowledge*. New York: New Left Books.

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What "scientific" means in 2019 may be very different from what it meant in 1919, 1819, or 1719. This doesn't mean that there aren't common threads that can be woven into a definition, and we shall endeavor to identify those threads. But the idea that universal factors must be present in all science over time – that science itself is not evolving – is a difficult position to support. But if science is evolving over time, is it a clearly definable thing? This, too, will be addressed.

Even if a clear and universally accepted distinction between science and nonscience that can categorize each and every instance does not exist, this does not mean that there is no difference between science and nonscience; the presence of gray does not eliminate the distinction between black and white. Insisting that no definition of science can be put forth unless it is perfect, identifying necessary and sufficient conditions, with no ambiguity or unclear instances, falls into the trap of black-and-white thinking (a.k.a., the perfect solution fallacy). In most cases, the world does not come in black and white, and attempts to force it into yes/no categories fails because the world is a continuum encompassing all shades. Nevertheless, even imperfect definitions can be both real and useful. In the translated words of Voltaire, "the perfect is the enemy of the good." For these reasons, ongoing examination of the black, the white, and the gray areas of this topic remains necessary.

More recently, a number of scholars have analyzed the definition of science with the recognition that absolute categories can simply be an artifact of language and human thinking and that previous failures to define science were inevitable unless one treats categories as more fluid and with boundaries that are less sharply defined.[6] It has been suggested that science vs. nonscience must be analyzed using looser boundaries, with families of properties or "cluster analysis."[7] Difficulty in categorization is by no means unique

[6] Dupré J. 1993. *The Disorder of Things: Metaphysical Foundations of the Disunity of Science*. Cambridge, MA: Harvard University Press.

[7] Mahner M. 2013. "Science and Pseudoscience: How to Demarcate after the (Alleged) Demise of the Demarcation Problem." In Pigliucci M, Boudry M (Eds.). *Philosophy of*

to science, it is a regrettable problem of language and thought and afflicts many areas – philosophers and linguists can at times have a very hard time precisely defining things that are nevertheless agreed to exist. Still, this in no way undermines the importance of refining definitions and continuing to characterize and describe. Defining what science is (and is not) remains a task of great importance.[8]

THE ILLUSION OF SCIENCE: A VERSION OF THE LEGEND LIVES ON

Science is often presented and perceived as a logical and orderly process that makes steady progress in understanding nature. Scientific presentations and publications are viewed in this fashion. Textbooks describe how seminal experiments were carried out to challenge scientific ideas from the past and how theories were adjusted to encompass new and surprising results. Scientific findings are reported with the appearance of being rational and logical as fields march steadily forward to better theories and greater understanding. Moreover, scientific beliefs are often stated as unequivocal facts. In 2012, when observations were made, consistent with what would be predicted if the Higgs boson existed, most reports didn't claim to have "encountered evidence consistent with the presence" of a Higgs boson; rather, it was stated that the Higgs boson had been "discovered"! In actuality, a scientific fact is nothing more than that which has stood up to rigorous testing thus far by the scientific methodologies currently available, but this is not how scientific facts are often presented.

Pseudoscience: Reconsidering the Demarcation Problem. Chicago and London: University of Chicago Press, pp. 29–43.

[8] For a review of the demarcation issue and its history, see Nickles T. 2006. "The Problem of Demarcation." In Sarkar S, Pfeifer J (Eds.). *The Philosophy of Science: An Encyclopedia. Vol 1.* New York: Routledge, pp. 188–197. See also Nickles T. 2013. "The Problem of Demarcation, History and Future." In Pigliucci M, Boudry M (Eds.). *Philosophy of Pseudoscience: Reconsidering the Demarcation Problem*. Chicago and London: University of Chicago Press, pp. 101–120.

In order to understand science, it is necessary to jettison the unrealistic hyperbole that has been mistakenly assigned to it (from a number of sources), and that has been perpetuated by practicing scientists and science enthusiasts. The flaws of science need to be called out, and greater attention must be directed to its problems, weaknesses, and the limits of what it can show us. We must turn the scientific microscope back on itself and dissect the specimen with a critical and analytic eye, without succumbing to the tendency to give descriptions that are unjustifiably favorable. By describing science as it really is, warts and all, we can simultaneously view science realistically and more accurately differentiate it from other ways of thinking. That science is imperfect and flawed doesn't mean that it isn't distinct from other knowledge systems or that it can't be described, if not defined. Likewise, its flaws and imperfections don't prevent it from being the most effective means (thus far) of exploring and understanding nature. Just as democracy may be "the worst form of government except for all the others,"[9] the same could be said for science's role in understanding the natural world. The goal of this book is to view science more realistically, not to make vain and misguided attempts to defend a grandiose view that is out of step with the actual entity.

The depiction of science as a logical and orderly process, governed by a specific method and leading to firm facts about nature, although regrettably a distortion of how science is really carried out, is the byproduct of how scientific findings are communicated among scientists. The reasons for this will be expanded upon later, but for now it's important to note that while such distortions may be necessary to communicate scientific findings efficiently, it is profoundly damaging to present this illusion of science rather than the reality of how it is practiced. Practicing scientists typically understand that the distortion does not reflect the reality of the situation. However, those

[9] This quote is attributed to Winston Churchill, but apparently he was quoting an earlier source that remains unidentified.

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outside a field (or outside science altogether) may miss this distinction, believing science to be other than it is. Indeed, this distortion has likely contributed to the genesis of the Legend in the first place. In trying to understand science we can mistake the mirage for the desert. We must be willing to accept that the tempting oasis is merely an image, and we must focus instead on understanding the desert itself, which is the reality of the situation.

MISSING THE FOREST FOR THE TREES

Attempts to describe and understand science have often focused on its component parts, which is a necessary process of any deep analysis of an entity. Efforts have been made to distinguish science from nonscience based on logical constructs, the sociology of science, the psychology of science, and the history of science. However, while each of these areas plays a central role in what it means to practice modern science, none of them tell us the whole story. Trying to understand science exclusively through analysis of its parts is like the ancient story of the three blind humans each studying a different part of an elephant.[10] The person feeling the legs may think it's a tree, the person feeling the tail may think it's a rope, and the person feeling the trunk may assume it's a snake. Each is correct in their observations, but to understand what an elephant really is requires a broader view that merges the component parts into a greater system. This has been recognized in recent decades, and academic disciplines that attempt to generate an overall synthesis of what science is and how it works have emerged.

Modern science is a combination of multiple working parts, including: advanced instrumentation and approaches to observation, human perception and cognition, computational analysis, the application of logic and reasoning, and the effect of social bodies on how

[10] This story can be found at least as far back as the Buddhist text *Udana 6.5* from the middle of the first millennium BCE (and likely earlier) (https://en.wikipedia.org/wiki/Blind_men_and_an_elephant).

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investigation is conducted and interpreted. To grasp modern science, each of these factors must be accounted for; we need to understand both the forest and the trees, as neither has its fullest meaning without the other. In the last century alone, technologies and methodologies have greatly increased the scope of what we can observe (and also misinterpret) in ways never before possible. Cognitive psychology has taught us much about common errors in human reasoning, perception, and observation. Computational capacity allows us to generate and analyze previously overwhelming volumes of data and to make comparisons and analyses far beyond the capacity of the human mind and, in doing so, to lead to new errors an individual human mind would have a hard time making. Statistics has made great strides in its ability to analyze levels of error and to quantify uncertainty, to determine the nature of underlying mechanisms by the distribution of data, and to evaluate associations. Philosophers of science and logic have provided us with a much clearer understanding of the strengths and shortcomings of reasoning than ever before, as well as novel insights into the nature of evidence and the extent to which one can actually verify or reject an idea. Sociologists and anthropologists have learned a great deal about the effect of group dynamics and scientific societies on thinking. Linguists and philosophers of language have identified sources of ambiguity and miscommunication. To understand the current limits of science, each of these must be examined.

The understanding that science is a complex machine, with multiple working parts that need to be understood both individually and in aggregate, is essential. One cannot understand how an internal combustion engine works as a whole without understanding the function of a spark plug. Yet the full implications of what a spark plug does are unintelligible without a preexisting understanding of the entire engine. To break into a circle of codependent knowledge such as this, one may have to visit, and then revisit, the parts and the whole. In this book, the different individual components of science are described first. Later chapters then illustrate the interactions of individual parts

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as a system. For this reason, the reader is encouraged to loop back to earlier parts of the book, if needed, during the development of the narrative. In this way, the full implications of the properties of the individual parts of science may become clearer in later sections, when the whole system is described.

SCIENCE IS AN EXTENSION OF HUMAN THINKING THAT ALSO VIOLATES ASPECTS OF HUMAN THINKING

Science is often portrayed as something very different from normal human behavior or thinking. It seems fair to suspect that science is indeed distinct from normal human thought in at least some ways; after all, most humans are not scientists. However, just because science may differ from typical thinking in some fundamental ways doesn't mean that it is entirely foreign to human cognition. Rather, only a very small number of differences between science and normal human thinking distinguish the two. This may explain part of the difficulty in attempting to demarcate science from nonscience. Because they are so closely related, it's easy to point to apparent exceptions that violate any potential distinction. In other words, defining characteristics attributed to science have been rejected by some precisely because it is easy to find the same characteristics in thinking that is agreed to be nonscientific. Likewise, thinking that is ubiquitous in nonscientific pursuits has been easy to identify as an important component of methods of practicing scientists. Large categorical differences between science and nonscience are not to be found; rather, the small differences between them hold tremendous weight but can also be difficult to pin down.

The differences between scientific and normal thinking, while small, are nevertheless both fundamental to science and also deeply baked into normal human cognition. This in part explains why scientists must undergo so much formal training; they must first become aware of certain normal human tendencies and then learn how to manage and/or overcome them. One must learn how to ignore certain

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parts of what it is to think like a human – a difficult task for a thinking human to accomplish. While humans have been on this Earth for a long time, modern science has only been an activity of ours for about 400 years. The generation of science has been a development of human understanding, not of biology – prehistoric humans had essentially the same brains we do today but didn't have advanced science and technology. Scientists are engaging in a learned practice no different than any technique or skill that is developed and refined over time. But the reasoning and thinking that has been learned have subtle but essential parts that are different than our natural (or traditional) reasoning, otherwise we would have had science all along. Exploration of these small differences is key, as well as developing an understanding that because they may violate our natural thinking they feel "wrong" or "counterintuitive," while actually being quite correct.

DEFLATING SCIENCE TO A REALISTIC AND THEREFORE DEFENSIBLE ENTITY

It is an aim of this work to deflate common scientific hyperbole to a realistic and therefore more defensible description. Despite its accomplishments, the ability of science to predict nature is always limited in multiple ways. Scientific predictions and conclusions can never be certain, never be perfect, are certainly never infallible – nothing is ever "proven"' in a formal sense of the word. Even things that science labels "Laws of Nature" are themselves reversible if later understanding arises that requires their modification or even wholesale rejection. Ironically, when combined with its other properties (and this is key), it is precisely the recognition of its own limits and imperfections and the practices to which such recognitions then give rise, that constitutes science's greatest strength.

There are many systems of belief that provide much better explanations of experience than does science. Indeed, some systems can explain why anything and everything occurs; science makes no such claim, and those who would suggest that science currently has these ambitions are misguided. Other systems often claim to know

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absolute truths; modern science does not, and in this way the Legend truly is dead. If a conceptual framework by which you can comfortably explain the whole world and all experience is your goal, if you are uncomfortable (or even just don't favor) wrestling long term with ignorance and confusion,[11] then science is not the instrument for this. Why then, you might ask, should one embrace science over other systems that claim to provide truth and explanation? The answer is that if the ability to predict and control nature is your goal, then the very science that fails to explain everything with the comprehensive certainty of other systems of belief outperforms everything else every day of the week and twice on Sunday. It is understanding how this flawed system can repeatedly make uncanny and correct predictions better than any other approach to knowledge yet described and to the opposite of what normal human inclinations and explanations would do – that is the goal of this work.

[11] In the book, *Ignorance,* a compelling argument is made that science focuses on ignorance more than knowledge – a key component that manifests itself in much of scientific practice. Firestein S. 2012. *Ignorance: How It Drives Science*. Oxford, UK: Oxford University Press.

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