A Beginner's Guide to Scientific Method

Third Edition

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Science

Science when well digested is nothing
but good sense and reason.

STANISLAUS

JUST WHAT IS SCIENCE?

We all have a passing familiarity with the world of science. Rarely does a week go by wherein a new scientific study or discovery is not reported in the media. "Astronomers confirm space structure that's mind-boggling in its immensity," and "Scientists identify gene tied to alcoholism," are the headlines from two recent stories in my daily newspaper. Another opened with the following: "A panel of top scientists has dismissed claims that radiation from electric power lines causes cancer, reproductive disease, and behavioral health problems." Yet many of us would be hard pressed to say much more about the nature of science than that science is whatever it is scientists do for a living. Hardly an illuminating account!

So, what more might we say in response to the question, "Just what is science?" We cannot hope to answer this question by looking at the subject matter of the sciences. Science investigates natural phenomena of every conceivable sort—from the physical to the biological to the social. Scientists study everything from events occurring at the time of the formation of the universe to the stages of human intellectual and emotional development to the migratory patterns of butterflies. Though in what follows we will often refer to "nature" or "the natural world" as that which science investigates, we must understand that the "world" of the scientist includes much more than our planet and its inhabitants. Judging by its subject matter, then, science is the study of very nearly everything.

Nor can we hope to answer our question by looking at the range of activities in which scientists engage. Scientists theorize about things, organize vast research projects, build equipment, dig up relics, take polls, and run experiments on everything from people to protons to plants. A description of science in terms of the sorts of things scientists typically do, then, is not going to tell us much about the nature of science, for there does not seem to be anything scientists typically do.

If we are to understand just what science is, we must look at science from a different perspective. We must ask ourselves, first, why scientists study the natural world, and, then we must look at the way in which scientific enquiry is conducted, no matter what its subject.

ASKING WHY

Of course, we cannot hope to give a simple, ubiquitous reason why each and every scientist studies the natural world. There are bound to be as many reasons as there are practicing scientists. Nevertheless, there is a single "why" underlying all scientific research. In general, scientists study the natural world to figure out why things happen as they do. We all know, for example, that the moon is riddled with craters. From a scientific point of view, what is of real interest is precisely why this should be so. What natural processes have led to the formation of the craters? At the most basic level, then, science can be defined by reference to this interest in figuring things out. So, an essential part of the answer to our question. "Just what is science?" involves the basic aim of science. *Science is that activity, the underlying aim of which is to further our understanding of why things happen as they do in the natural world.* To see what it is that scientists do in attempting to "make sense" of nature, let's take a look at an historical instance that, as it turns out, played an important role in the development of modern medicine.

Up until the middle of the nineteenth century, little was known about the nature of infectious diseases and the ways in which they are transmitted. In the mid-eighteen hundreds, however, an important clue emerged from the work of a Viennese doctor, Ignaz Semmelweis. At the time, many pregnant women who entered Vienna General Hospital died shortly after having given birth. Their deaths were attributed to something called "childbed fever." Curiously, the death rate from childbed fever in the hospital ward where the patients were treated by physicians was five time higher than in another ward where women were seen only by midwives. Physicians were at a loss to explain why this should be so. But then something remarkable occurred. One of Semmelweis's colleagues cut his finger on a scalpel that had been used during an autopsy. Within days, the colleague exhibited symptoms remarkably like those associated with childbed fever and shortly thereafter died. Semmelweis knew that physicians often spent time with students in the autopsy room prior to visiting their patients in the maternity ward.

Thanks largely to the clue provided by the death of his colleague, Semmelweis speculated that something like the following might be responsible for the glaring differences in death rates in the two wards. Childbed fever was caused by something that physicians came into contact with in the autopsy room and then inadvertently transmitted to pregnant women during the course of their rounds in the maternity ward. Semmelweis appropriately termed this something, "cadaveric matter."

The challenge faced by Semmelweis was to devise a way of testing his ideas about the link between cadaveric matter and childbed fever. Semmelweis reasoned as follows: If childbed fever is caused by cadaveric matter transmitted from physician to patient, and if something were done to eradicate all traces of cadaveric matter from the physicians prior to their visiting patients in the maternity ward, then the incidence of childbed fever should diminish. In fact, Semmelweis arranged for physicians to wash their hands and arms in chlorinated lime water—a powerful cleansing agent—prior to their rounds in the maternity ward. Within two years, the death rate from childbed fever in the ward attended by physicians approached that of the ward attended by midwives. By 1848, Semmelweis was losing not a single women to childbed fever!

SCIENTIFIC METHOD

At its most basic level, scientific method is a simple, three-step process by which scientists investigate nature. Begin by carefully observing some aspect of nature. If something emerges that is not well understood, speculate about its explanation and then find some way to test those speculations. Each step—observing, explaining, and testing—is nicely illustrated by the historical event we have just described.

Observing

Before we can begin to think about the explanation for something we must make sure we have a clear sense of the facts surrounding the phenomenon we are investigating. Semmelweis's explanation of childbed fever was prompted by a number of facts, each the product of careful observation: First, the fact that the rates of childbed fever differed in the wards in question; second, that patients in the ward where the rate was the highest were treated by physicians, not midwives; and finally the remarkable symptoms of his dying colleague.

Getting at the facts can both help us to establish the need for a new explanation and provide clues as to what it might involve. Suppose, for example, that careful long-term observation revealed to Semmelweis that on average the death rates were about the same in the two wards. In some months or years the rate was higher in one ward, in others, higher in the other. In these circumstances nothing puzzling needs to be accounted for—the original set of observations would seem to be nothing more than the sort of brief statistical fluctuation that is bound to occur now and then in any long series of events. But as Semmelweis found, the difference in death rates was not a momentary aberration. Thus, by careful observation Semmelweis was able to establish that something not fully understood was going on. It was Semmelweis's good fortune to then make the key observation that suggested what might be responsible for the problem—the unusual similarity between the symptoms of the dying mothers and his sick colleague.

Proposing Explanations

To explain something is to introduce a set of factors that account for how or why the thing in question has come to be the case. Why, for example, does the sun rise and set daily? The explanation is that the earth rotates about its axis every twenty-four hours. When something is not well understood, its explanation will be unclear. Hence the first step in trying to make sense of a puzzling set of facts is to propose what we might call an explanatory story—a set of conjectures that would, if true, account for the puzzle. And this is precisely what Semmelweis set about doing. Semmelweis's explanatory story involved the claims that something in cadaveric matter causes childbed fever and that this something can be transmitted from cadaver to physician to patient by simple bodily contact.

Semmelweis's explanation was all the more interesting because it introduced notions that were at the time themselves quite new and puzzling—some very new and controversial ideas about the way in which disease is transmitted. Many of Semmelweis's contemporaries, for example, believed that childbed fever was the result of an epidemic, like the black plague, that somehow infected only pregnant women. Others suspected that dietary problems or difficulties in the general care of the women were to blame. Thus, in proposing his explanation, Semmelweis hinted at the existence of a new set of explanatory factors that challenged the best explanations of the day, and which had the potential to challenge prevailing views about how diseases are spread. All that remained for Semmelweis was to find a way to test his explanation.

Testing Explanations

How can we determine whether a proposed explanation is correct or mistaken? By the following strategy. First, we look for a consequence of the explanation—something that ought to occur, if circumstances are properly arranged and if the explanation is on the right track. Then we carry out an experiment designed to determine whether the predicted result actually will occur under these circumstances. If we get the results we have predicted, we have good reason to believe our explanation is right. If we fail to get them, we have some initial reason to suspect we may be wrong or, at the very least, that we may need to modify the proposed explanation.

This was precisely the strategy Semmelweis employed in testing his ideas about the cause of childbed fever. If something physicians have come into contact with prior to entering the maternity ward is causing the problem and if this "something" is eradicated, then it follows that the rate of childbed fever should drop. And, indeed, once these circumstances were arranged, the out-come predicted by Semmelweis occurred. As a result, he was confident that his initial hunch was on the right track. By contrast, had there been no reduction in the rate of childbed fever as a result of the experiment, Semmelweis would at least have had a strong indication that his hunch was mistaken.

At the most basic level, the scientific method is nothing more than the simple three-step process we have just illustrated—carefully observing some aspect of nature, proposing and then testing possible explanations for those observational findings that are not well understood. In the chapters to follow we will need to add a great deal of detail to our initial sketch of scientific method. We will come to recognize that scientific method is not all that straightforward nor, for that matter, easy to apply. Explanations are not always as readily tested as our initial examples might suggest nor are test results always as decisive as we might like them to be. We will also find that, with some minor variations, scientific method can be used to test interesting and controversial claims as well as explanations. For now, however, we can use what we have discovered about scientific method to get at the remainder of the answer to our opening question.

Just what is science? *Science is that activity, the underlying aim of which is to further our understanding of why things happen as they do in the natural world. It accomplishes this goal by applications of scientific method—the process of observing nature, isolating a facet that is not well understood, and then proposing and testing possible explanations.*

THE CONSEQUENCES OF SCIENCE

Before moving on, an important caveat is in order. In focusing on the preoccupation of science with making sense of nature—of providing and testing explanations—we have ignored what is surely an equally compelling interest of the sciences, namely, making the world a better place to live via technological innovation. Indeed, when we think of science, we often think of it in terms of some of its more spectacular applications: computers, high speed trains and jets, nuclear reactors, microwave ovens, new vaccines, etc. Yet, our account of what is involved in science is principally an account of science at the theoretical level, not at the level of application to technological problems.

Don't be misled by our use of the term "theoretical" here. Theories are often thought of as little more than guesses or hunches about things. In this sense, if we have a theory about something, we have at most a kind of baseless conjecture about the thing. In science, however, "theory" has a related though different meaning. Scientific theories may be tentative, and at a certain point in their development will involve a fair amount of guesswork. But what makes a scientific theory a theory is its ability to explain, not the fact that at some point in its development it may contain some rather questionable notions. Much as there will be tentative, even imprecise, explanations in science, so also will there be secure, well established explanations. Thus, when we distinguish between theory and application in science we are contrasting two essential concerns of science: concern with understanding nature, and concern with exploiting that theoretical understanding as a means of solving rather more practical, technological problems.

Yet there is an important, if by now obvious, connection between the worlds of theoretical and applied science. With very few exceptions, technical innovation springs from theoretical understanding. The scientists who designed, built, and tested the first nuclear reactors, for example, depended heavily on a great deal of prior theoretical and experimental work on the structure of the atom and the ways in which atoms of various sorts interact. Similarly, as the case we have been discussing should serve to remind us, simple but effective new procedures for preventing the spread of disease were possible only after the theoretical work of Semmelweis and others began to yield some basic insight into the nature of germs and the ways in which diseases are spread.

SCIENTIFIC METHOD IN DAILY LIFE

The brief sketch of scientific method given above may have a familiar ring to it and for good reason. To a large extent thinking about things from a scientific perspective—thinking about the "hows" and "whys" of things—involves nothing more than the kind of problem solving we do in our daily lives.

To see this, imagine the following case. For the last few nights, you haven't been sleeping well. You've had a hard time getting to sleep and have begun waking up frequently during the course of the night. This is unusual, for you are normally a sound sleeper. What could be causing the problem? Well, next week is final exam week and you have been staying up late every evening, studying. Could concern about your upcoming exams be causing the problem? This seems unlikely, since you have been through exam week several times before and have had no problems sleeping. Is there anything else unusual about your behavior in the last few nights? It has been quite warm, so you have been consuming large quantities of your favorite drink, iced tea, while studying. And this could explain the problem. For you are well aware that most teas contain a stimulant, caffeine. It may well be the caffeine in your iced tea that is disturbing your sleep! But is this the right explanation? Here, a relatively quick, easy, and effective test can be performed. You might, for example, try drinking ice water instead of iced tea in the evening. If you were to do this, and if you again began sleeping normally, we would have good reason to think that our explanation was right; it must be the caffeine in the iced tea. Moreover, if you were not to begin sleeping normally we would have some reason to suspect that we have not yet found the right explanation; eliminating the caffeine didn't seem to do the trick.

Though nothing of any great scientific consequence turns on the solution of our little puzzle, the solution nevertheless is a straightforward application of scientific method: observing something unusual, venturing a guess as to what its explanation might be, and then finding a way to test that guess.

THINGS TO COME

In the chapters to follow, our central concern with be to expand the preliminary sketch of scientific method given so far. Along the way, we will pay particular attention to the pitfalls scientists are likely to encounter in making accurate observations and in designing and carrying out decisive experimental tests. On our agenda will be a number of controversial topics, perhaps none more so than the distinction between legitimate and fraudulent applications of scientific method. Nothing can do more to lend an air of credibility to a claim than the suggestion that it has been "proven in scientific studies" or that it is "backed by scientific evidence." A sad fact, however, is that many claims made in the name of science are founded on gross misapplications of some aspect of scientific method. Indeed, so numerous are the ways in which scientific method can be abused that we will find it necessary to devote a chapter to fallacies commonly committed under the guise of scientific research.

Our goals, then, in the chapters to follow are twofold. Our first and most important goal is to become familiar with the basic methodology common to all good scientific research. Our second goal is to learn to distinguish between legitimate and bogus applications of scientific method. Having accomplished these goals, I think you will find yourself quite capable of thinking clearly and critically about the claims of scientists and charlatans alike to have advanced our understanding of the world about us.

EXERCISES

Try your hand at telling explanatory stories. The following exercises all describe curious things. See if you can come up with one or two explanations for each. Keep in mind, your explanation need not be true but it must be such that it would explain the phenomena in question, if it were true.

1. A survey done recently revealed that whereas 10 percent of all 20-year-olds are left-handed, only about 2 percent of all 75-year-olds are left-handed.
2. Have you ever noticed that baseball players tend to be quite superstitious? Batters and pitchers alike often run through a series of quite bizarre gestures before every pitch.
3. Americans have a serious weight problem. In the last decade, both the number of Americans who are overweight and who are clinically obese has increased by more than 10 percent. The increase over the last two decades in both is nearly 20 percent.
4. Why have so many Americans switched from driving sedans to sports utility vehicles and trucks in the last few years?
5. We all know what happens when we depress the handle on a toilet. The flapper inside the tank opens and water rushes into the bowl, flushing it out and refilling the bowl. But what keeps the fresh water in the bowl?