A Short Course in the Scientific Method

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Let's have a short review of the scientific method, shall we?

Most people have heard the phrase but have only a vague idea of what it means. It's something about men and women in lab coats fooling around with test tubes, torturing white rats and such.

Fortunately for white rats, that description is almost entirely inaccurate.

Even scientists, however, often misunderstand the nature of what they're doing and its limitations. Popular science writers are even worse. So a review of the basics is in order.

How the Scientific Method Works

The scientific method is a process consisting of observation, hypothesis ("suppose that X is true"), testing ("If X is true, then we'll see Y"), and repeated testing ("Yes, in this case, we see Y" or "No, in this case, we don't see Y").

Here's an example of the scientific method in action:

- I observe that an apple is red.
- In the next five cases, I observe apples and they are all red.
- I form a hypothesis: "All apples are red."
- I and other people test the hypothesis under different conditions, in different places, at different times, and with different types of apples.
- We find one of two things: Either (a) all the apples we look at are red, which confirms our hypothesis; or (b) we find at least one non-red apple, which disproves our hypothesis.

As long as we're on the subject, notice the different words used in cases (a) and (b). If we find only red apples, that confirms the hypothesis. It doesn't prove it. There could still be some non-red apples, but we just haven't found them yet. On the other hand, if we find even one non-red apple, that disproves the hypothesis that "all apples are red." Then we know that the hypothesis is false.

When a hypothesis has been confirmed by all known observations, we consider it well established. At that point, we might promote it to the status of a generalization, law, or theory. A theory differs from a generalization or law because it doesn't just summarize observed facts: it also tries to explain them in terms of other facts that we haven't yet observed. When we go looking for those unobserved facts, we're testing the theory.

But whether something is a generalization, law, or theory, it's still only been confirmed, not proven. Even a "law" can be revised or rejected in the light of new evidence or a more insightful analysis.

Human Nature Distorts the Process

Sometimes, new observations aren't even needed. For broad theories, there are often little observations at the margins that don't quite fit the theories. In those cases, most people tend to follow the theory. They either ignore the observations that don't fit, they dismiss them as unreliable, or they try somehow to cram them into the theory so that they fit.

What most people don't realize is that human beings, even scientists, are not purely dispassionate thinking machines. If they've spent years researching and confirming a theory, they've got both their egos and years of their lives invested in it. So do other scientists. To question conventional wisdom is to question the validity of one's own work and risk ostracism by one's peers. Understandably, and quite reasonably in terms of their own mundane self-interest, most people just don't want to do that. So even if they have private doubts, they defend conventional wisdom against all comers.

This human tendency isn't a new thing. You've probably heard of the Pythagorean theorem: in a right triangle, the square of the hypotenuse (the longest side) is equal to the sum of the squares of the other two sides. What you probably haven't heard is that Pythagoras and his followers believed everything could be explained by integers (whole numbers) and ratios of integers (fractions). "Ratio" is where we get the word "rational," so in other words, the Pythagoreans believed that the world was rational. Note that any whole number can also be expressed as a ratio, such as 15/15 or 1/1.

But Pythagoreans had a terrible shock when they discovered that some quantities could not be expressed as whole numbers or ratios. In particular, if a right triangle's shorter sides each have length 1, then the hypotenuse length is the square root of 2. The square root of 2 cannot be expressed as a whole number or as a ratio: it is irrational.

And the Pythagoreans did what most scientists do when they run into an observation that conflicts with a cherished theory: They ignored it. They still believed that they could explain the world entirely by rational numbers (integers and ratios), but there was also this "other thing" (irrational numbers) that they just tried not to think about.

The same thing happened at the end of the 19th century. With classical mechanics, essentially a more sophisticated and developed version of Isaac Newton's worldview, scientists -- and pretty much everyone else, if the truth be told -- thought that they had the world completely figured out. But there were these little observations at the margin. Odd things that the theory couldn't quite explain: for example, that according to observations based on the theory, the earth wasn't moving through space. But even the greatest scientists of the era, such as Lord Kelvin, tried to ignore those results on the assumption that someday they'd be explained.

And Albert Einstein did explain them, but he explained them in a way that the scientific community didn't like: He said that classical mechanics was wrong.

Einstein didn't do any new experiments. He just took the marginal observations seriously and came up with a new way of looking at space and time. Most scientists up to the 1930s thought he was a crank. Einstein's theories didn't gain wide acceptance until the old generation of physicists died off: I have a book from the 1930s called *Back to Newton*, by an old-guard physicist who tried to debunk Einstein's view. After that, a new, more open-minded generation embraced Einstein's ideas.

Paradigm Shifts

What happened when mathematicians finally accepted irrational numbers, and when physicists finally accepted Einstein's relativity theories, is called a paradigm shift. It's not just a little change in this theory or that theory. It's a change in our whole way of looking at the world: that is, it's acceptance of a new worldview.

That worldview provides the context for development of theories about more specific aspects of reality. It provides a foundation for new theories, but it also biases them in the same way as the Pythagorean view and classical mechanics biased people when they were the dominant viewpoints. So even under the new paradigm, there will still be little observations around the margin that don't quite fit. The process starts all over again.

Sooner or later, those marginal observations lead to a new paradigm that's slightly more accurate, and then to another, on and on. Reality is infinite, so we never get to the end. What would be the fun in that?

What the Scientific Method Does Not Tell Us

Let's get back to the example of the apples:

- I observe that an apple is red.
- In the next five cases, I observe apples and they are all red.
- I form a hypothesis: "All apples are red."
- I and other people test the hypothesis under different conditions, in different places, at different times, and with different types of apples.
- We find one of two things: Either (a) all the apples we look at are red, which confirms our hypothesis; or (b) we find at least one non-red apple, which disproves our hypothesis.

So far, so good. That's all entirely justified and reasonable. But what if we then wanted to draw a further conclusion:

- We've observed apples.
- Therefore, only apples exist. Grapes, bananas, and oranges are figments of deluded people's imaginations. Those observations aren't reliable at all.

We might reach such a conclusion, but it would not be justified by the scientific method.

Using the Scientific Method

The scientific method is a reliable tool for acquiring knowledge about the physical world. As long as we are aware of its limitations, it will serve us well in any area of knowledge.