

Chapter 4

How to Think Like a Scientist

*Science is a way of thinking much more
than it is a body of knowledge.*

Carl Sagan

By the time you've made it to grad school, you should be well acquainted with the principles of the scientific method. Most likely the concepts have been drilled into you ever since high school biology class. Even so, we felt it wouldn't be a bad idea to review some of the principles here, as they will form the core of your work in the lab. Over the years, well-meaning friends and family members have probably asked this deceptively simple question: "So what does a scientist do anyway?" or "Tell me about your research." You may or may not have a ready answer depending on who is doing the asking and how much explaining you want to do. But imagine you are sitting around the dinner table and have been asked this question by a family member or friend, someone who knows nothing about scientists or the scientific method. How would you respond in a way that was clear and made sense to the non-scientist?

Perhaps the simplest and most accurate answer you could formulate is that scientists observe and measure the world around them (yes, you may use this the next time you're asked, unless you have a much wittier answer and then we'd love to hear it). They gather information or data based on their observations, and when they think they have enough to answer the questions they have asked, they try to make sense of what it all means.

During this process, most scientists use a reductionist approach. Let's say one scientist is studying a complex chemical reaction, another is investigating the foraging behaviour of the ring-tailed lemur, and a third is researching the ocean currents around Tierra del Fuego. In order to make sense of these very complicated phenomena, each of

these scientists must break down the particular problem into simple components. These four components are usually given as follows:

- Observation
- Constructing a hypothesis
- Carrying out experiments to test the hypothesis
- Formulating a theory

These four steps, taken together, are what is commonly known as the scientific method. If carried out correctly, the ultimate goal of the scientific method is to construct an accurate representation of the physical world. You may already have learned about the scientific method at some point in your career as a student of science, and while it may all seem very theoretical, it will be important to keep these steps in mind as you go about your own research.

Because scientists may be unduly influenced by personal and cultural beliefs and assumptions, which may alter their perceptions and interpretations of the natural world, the scientific method, if rigorously followed, can be considered an attempt to minimize bias on the part of the scientist. That doesn't mean, however, that the scientific method is without pitfalls.

Common errors in using the scientific method

Not proving the hypothesis by experiment

Perhaps the most fundamental error a scientist can make is to mistake the hypothesis for an explanation of a phenomenon *without* having performed any experimental tests to verify the hypothesis. Sometimes what we think of as common sense, logic, or intuition tempts us into believing that no experimental proof is necessary to prove the hypothesis because the answer seems so obvious from the start. Consider a classic mistake made by the philosopher, Aristotle, who many people consider to be the father of the scientific method. He emphatically stated that women have fewer teeth than men (probably to support his argument that men were superior). He never actually tried to prove this fact; he just used this misconception as a way to

prove what everybody in ancient Greece accepted at face value anyway (that men are superior to women!). Now we all know that adult men and women have the exact same number of teeth – so don't fall into the same trap as Aristotle. Use properly designed experiments to prove your hypothesis, rather than rely on 'obvious' assumptions.

Discounting data that don't support the hypothesis

Another common mistake is to ignore data that do not support your hypothesis. In the ideal situation, the scientist is open to the possibility that the hypothesis is either correct or incorrect. If, for example, the researcher has a strong belief that the hypothesis is true or false, before collecting any experimental data, there may be a psychological tendency to find something 'wrong' with any data that does not support the researcher's expectations. It's hard to get rid of all our biases at once. The important point to keep in mind is that you need to treat all data the same way.

A third type of common mistake occurs when systematic errors are either over- or underestimated. For example, many discoveries were missed by researchers whose data pointed to a new phenomenon, but the data were mistakenly attributed to 'experimental noise.' Conversely, data that is part of the normal variation of the experimental process was taken as evidence for a new discovery.

How can this tendency towards bias be reduced? An important check on bias is to promote open communication among the members of a scientific field in the form of publications and conferences. In this way, the biases of individuals will most likely be cancelled out as other scientists try to reproduce their results. In time, a consensus may develop in the research community as to which experimental data has withstood the test of time.

Fact, theory, hypothesis – what's the difference anyway?

These terms are not interchangeable, even though they are often treated that way in popular usage. For a scientist, each of these terms has a specific definition:

A **fact** is a thing that is known to be true. Fire burns wood into ash. Water is solid (frozen) at temperatures below zero degrees Celsius.

A **theory** is a conceptual framework that can be used to explain existing observations and predict new ones. For example, the path the sun follows as it crosses the sky can be explained by the theory of gravity.

A **hypothesis** is a working assumption. Usually this assumption is formulated *before* experiments are carried out to test it. If the hypothesis holds up against existing and newly obtained data, the scientist may formulate it as a theory.

Is there ever a time when the scientific method is not applicable?

A frequent criticism of the scientific method is that it cannot accommodate anything that has not already been proved. This argument points out that many things thought to be impossible in the past are now everyday realities (such as space travel, for example: Two hundred years ago it was believed impossible for humans to fly to the moon). This criticism, however, is based on a misunderstanding of the scientific method. When a hypothesis passes the test, it is adopted as a theory, which can correctly explain a range of phenomena. This theory, however, can always be falsified by new experimental evidence. But it is not necessary for the hypothesis to have been previously proved for the scientific method to work.

Ockham's razor

In the fourteenth century, William of Ockham proposed the principle now known as Ockham's razor, which he stated as: *Pluralitas non est ponenda sine necessitate*. This can be translated as: Entities should not be multiplied unnecessarily. In other words, 'keep it simple'.

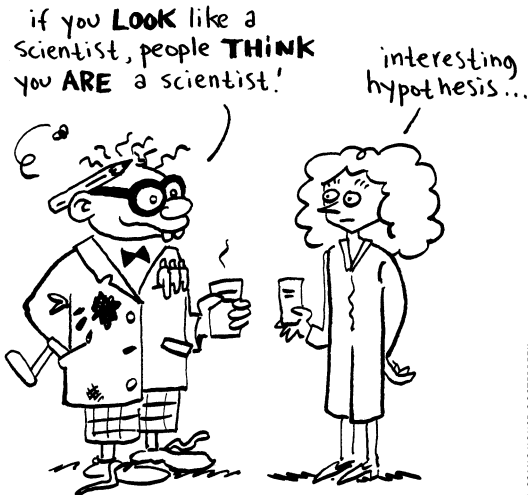
Suppose, for example, you have two theories that predict the same thing. In this instance, the principle of Ockham's razor can come in handy. Here are two sample theories that describe the same phenomenon:

- The tides on earth are influenced by the position of the moon.
- The tides on earth are influenced by the position of the moon, which is determined by the will of a powerful supernatural being.

Both theories make identical predictions, but Ockham's razor would discount the second theory as containing unnecessary information. The simpler theory works just as well. Ockham's razor does *not* guarantee, however, that the simplest theory will be correct, it merely establishes priorities.

A final comment

Biases aside, the scientific method is the best approach we have to accurately answer questions about the physical world in which we live. Without the scientific method, we might still believe in the idea of spontaneous generation (that flies, for example, are 'born' out of rotten meat), a theory that was disproved by Francesco Redi and Louis Pasteur in an ingenious experiment using the principles of the scientific method. As a result of his experiments Pasteur concluded that there is no life force in air, and organisms do not arise by spontaneous generation [from rotten meat] in this manner. "Life is a germ, and a germ is Life. Never will the doctrine of spontaneous generation recover from the mortal blow of this simple experiment."



Saving an Old Master painting: Isabel forms hypotheses about the whitish, transparent inclusions in the red paint

To prepare for her work in the lab, Isabel has been doing a lot of reading in the library on the chemistry of paintings and some of the problems that paintings undergo after several centuries of being exposed to light, air, humidity and extremes of temperature. In her reading she has discovered that some degradation can be the result of the formation of lead-soap aggregates of certain pigments, including red lead-containing paints. These lead-soap aggregates can expand and remineralize, changing their chemical composition. Because of some other evidence found on the painting, such as the break up of the overlying paint layer and whitish opaque material protruding through the surface of the painting, Isabel hypothesizes that aggregates have formed and have remineralized to lead carbonate, a remineralization product. If this is the case, she hypothesizes further that the red lead reacted with fatty acids released by the ageing of the oil binding medium. In order to prove her hypotheses, she elects to analyze the paint sample with a number of imaging techniques including FTIR, SEM/EDX and SIMS, selecting the appropriate technique to determine whether lead-soap aggregates have indeed formed, if they have subsequently remineralized and if this remineralization product is indeed lead carbonate.