1.3: Using the Scientific Method

Learning Objectives

- To identify the components of the scientific method
- Classify measurements as being quantitative or qualitative.
- Evaluate science in the media.

The Scientific Method

Scientists search for answers to questions and solutions to problems by using a procedure called the **scientific method**. This procedure consists of making observations, formulating hypotheses, and designing experiments, which in turn lead to additional observations, hypotheses, and experiments in repeated cycles (Figure 1.3.1).

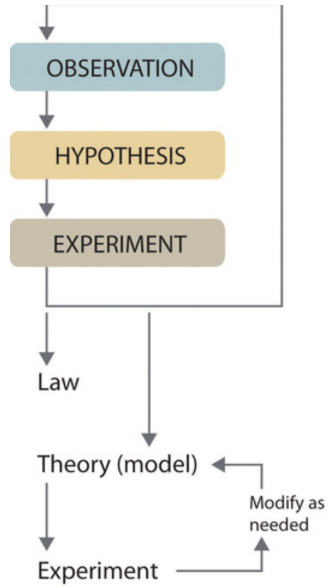


Figure 1.3.1: The Steps in the Scientific Method. (CC BY-SA-NC; anonymous).

Step 1: Make observations

Observations can be qualitative or quantitative. **Qualitative observations** describe properties or occurrences in ways that do not rely on numbers. Examples of qualitative observations include the following: the outside air temperature is cooler during the winter season, table salt is a crystalline solid, sulfur crystals are yellow, and dissolving a penny in dilute nitric acid forms a blue solution and a brown gas. **Quantitative observations** are measurements, which by definition consist of both a number and a unit. Examples of quantitative observations include the following: the melting point of crystalline sulfur is 115.21° Celsius, and 35.9 grams of table salt—whose chemical name is sodium chloride—dissolves in 100 grams of water at 20° Celsius. For the question of the dinosaurs' extinction, the initial observation was quantitative: iridium concentrations in sediments dating to 66 million years ago were 20–160 times higher than normal.

Step 2: Formulate a hypothesis

After deciding to learn more about an observation or a set of observations, scientists generally begin an investigation by forming a **hypothesis**, a tentative explanation for the observation(s). The hypothesis may not be correct, but it puts the scientist's understanding of the system being studied into a form that can be tested. For example, the observation that we experience alternating periods of light and darkness corresponding to observed movements of the sun, moon, clouds, and shadows is consistent with either of two hypotheses:

a. Earth rotates on its axis every 24 hours, alternately exposing one side to the sun, or
b. the sun revolves around Earth every 24 hours.

Suitable experiments can be designed to choose between these two alternatives. For the disappearance of the dinosaurs, the hypothesis was that the impact of a large extraterrestrial object caused their extinction. Unfortunately (or perhaps, fortunately), this hypothesis does not lend itself to direct testing by any obvious experiment, but scientists can collect additional data that either support or refute it.

Step 3: Design and perform experiments

After developing a hypothesis, scientists design and conduct experiments to test its validity. **Experiments** are systematic methods of making observations or measurements under controlled conditions, ideally with only one variable altered at a time. This approach allows researchers to isolate the effects of one variable on another in a clear, structured environment.

In any experiment, two primary types of variables are involved:

> **Independent Variable:** This is the variable that the scientist changes deliberately to observe its effect. It's the cause part of cause and effect.
>
> **Dependent Variable:** This variable is what the scientist measures or observes. It's the effect that is potentially influenced by changes in the independent variable.

Experiments typically have at least two groups:

> **Control Group:** This group does not receive the experimental treatment or change in the independent variable. It serves as a baseline to compare the effects of the independent variable. Some experiments include things called **positive controls** and **negative controls**. These are slightly different from control groups. Positive and negative controls serve to show that the experiment is working correctly. A positive control is a part of the experiment that is deliberately designed to give a positive result. It shows that the experiment is capable of producing a positive result when it is supposed to. A negative control is a part of the experiment that is designed to give a negative result. It shows that the experiment is capable of producing a negative result when it is supposed to.
>
> **Treatment Group(s):** In these groups, the independent variable is manipulated to various degrees, allowing the scientist to observe the changes that occur in the dependent variable.

After the experiment, scientists collect data, often quantifying it in graphs or tables for analysis. This data analysis helps determine if there is a statistical relationship between the dependent and independent variables, thereby supporting or refuting the hypothesis.

Step 4: Accept or modify the hypothesis

A properly designed and executed experiment enables a scientist to determine whether the original hypothesis is valid. In which case he can proceed to step 5. In other cases, experiments often demonstrate that the hypothesis is incorrect or that it must be modified thus requiring further experimentation.

Step 5: Development into law and/or theory

More experimental data are then collected and analyzed, at which point a scientist may begin to think that the results are sufficiently reproducible (i.e., dependable) to merit being summarized in **law**, a verbal or mathematical description of a phenomenon that allows for general predictions. A law simply says what happens; it does not address the question of why.

One example of a law, the law of definite proportions, which was discovered by the French scientist Joseph Proust (1754–1826), states that a chemical substance always contains the same proportions of elements by mass. Thus, sodium chloride (table salt) always contains the same proportion by mass of sodium to chlorine, in this case, 39.34% sodium and 60.66% chlorine by mass, and sucrose (table sugar) is always 42.11% carbon, 6.48% hydrogen, and 51.41% oxygen by mass.

Whereas a law states only what happens, a **theory** attempts to explain why nature behaves as it does. Laws are unlikely to change greatly over time unless a major experimental error is discovered. In contrast, a theory, by definition, is incomplete and imperfect, evolving with time to explain new facts as they are discovered.

Because scientists can enter the cycle shown in Figure $1.3.1$ at any point, the actual application of the scientific method to different topics can take many different forms. For example, a scientist may start with a hypothesis formed by reading about work done by others in the field, rather than by making direct observations.

A Real-World Application of the Scientific Method

In 2007, my husband and I journeyed to China to adopt our daughter. Upon arrival in Beijing, I became violently ill. Due to her visa paperwork, my husband, daughter, and I were required to stay in China for two weeks. Unfortunately, I was ill the entire time. Once the two-week period was up, the three of us flew back to the United States where I continued to be sick. For the next year, I remained ill and lost a total of 30 pounds. The picture below shows me holding my daughter eight months after we returned home from China.

I would like you to attempt to perform the scientific method on my situation described above. List the steps of the scientific method along with some plausible explanations. * Please have this ready to discuss in class.*

✓ Exercise (PageIndex{1})

Classify each statement as a law, a theory, an experiment, a hypothesis, a qualitative observation, or a quantitative observation.

a. Ice always floats on liquid water.
b. Birds evolved from dinosaurs.
c. According to Albert Einstein, mass X speed of light = energy
d. When 10 g of ice was added to 100 mL of water at 25°C, the temperature of the water decreased to 15.5°C after the ice melted.
e. The ingredients of Ivory soap were analyzed to see whether it really is 99.44% pure, as advertised.

Solution

a. This is a general statement of a relationship between the properties of liquid and solid water, so it is a law.
b. This is an educated guess regarding the origin of birds, so it is a hypothesis.
c. This is a theory that explains an explanation of events and can be disproven at any time.
d. The temperature is measured before and after a change is made in a system, so these are quantitative observations.
e. This is an analysis designed to test a hypothesis (in this case, the manufacturer's claim of purity), so it is an experiment.

? Exercise (PageIndex{2})

Classify each statement as a law, a theory, an experiment, a hypothesis, a qualitative observation, or a quantitative observation.

a. Measured amounts of acid were added to a Rolaids tablet to see whether it really "consumes 47 times its weight in excess stomach acid."
b. Heat always flows from hot objects to cooler ones, not in the opposite direction.
c. The universe was formed by a massive explosion that propelled matter into a vacuum.
d. Michael Jordan is the greatest pure shooter ever to play professional basketball.
e. Limestone is relatively insoluble in water but dissolves readily in dilute acid with the evolution of a gas.
f. Gas mixtures that contain more than 4% hydrogen in air are potentially explosive.

Answer a: experiment

Answer b: law

Answer c: theory

Answer d: hypothesis

Answer e: qualitative observation

Answer f: quantitative observation

? Exercise 1.3.1

Classify each statement as a law, a theory, an experiment, a hypothesis, a qualitative observation, or a quantitative observation.

a. When 10 g of ice were added to 100 mL of water at 25 °C, the temperature of the water decreased to 15.5 °C after the ice melted.
b. Litmus paper dipped in lemon juice turns red.
c. A prism separates white light into a spectrum of colors.
d. Limestone is relatively insoluble in water but dissolves readily in dilute acid with the evolution of a gas.
e. Gas mixtures that contain more than 4% hydrogen in air are potentially explosive.

Answer a: quantitative observation

Answer b: qualitative observation

Answer c: qualitative observation

Answer d: qualitative observation

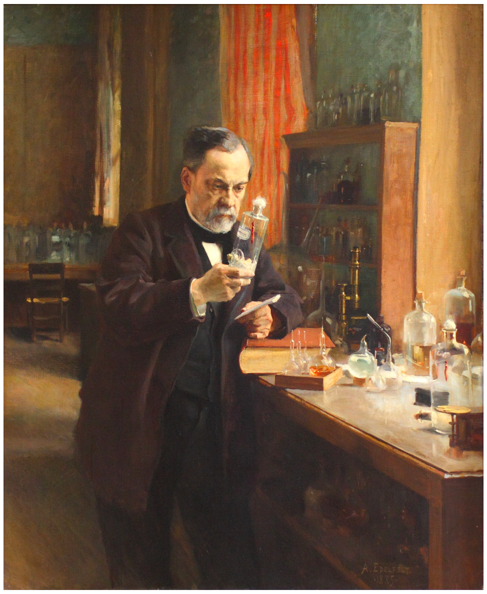
Answer e: quantitative observation

The Scientific Methods: Crash Course History of Science #14

One famous example is the experiment conducted by Louis Pasteur to test the hypothesis of **spontaneous generation**. This was the once popular idea that non-living material can spontaneously transform into living organisms. For example, if meat were left out too long, people would find that it was infested with maggots. Many people assumed that the meat was transforming into live maggots. After the discovery of microorganisms like bacteria, people questioned where they came from. Were they being spontaneously generated or were they reproducing? In other words, did microorganisms produce new microorganisms?

To test the hypothesis of spontaneous generation, Pasteur devised a simple but ingenious experiment. He filled two flasks with chicken broth. One was an open-necked flask, and the other was a swan-necked flask. The open-necked flask would allow bacteria from the air to enter the broth. On the other hand, the swan-necked flask would trap any bacteria in the elbow of the neck, thus preventing the bacteria from reaching the broth. He then boiled both broths to sterilize them. If spontaneous generation was valid, it should not have mattered whether bacteria from the outside were able to enter the broth. There should be bacteria growing in both flasks.

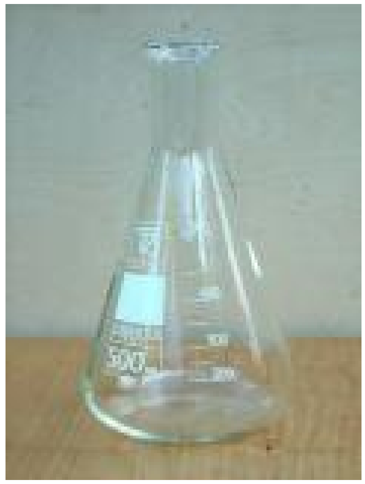
On the other hand, if bacteria only came from the outside, then only the open-necked flask should have bacteria growing it. After a few days, Pasteur examined the broth in both flasks and found only new bacteria growing in the open-necked flask. Since the swan-neck flask did not show any bacteria growing in it, the hypothesis of spontaneous generation was rejected, and we now know that for maggots to grow on meat, flies must first lay their eggs on the meat. The maggots then hatch out of the eggs and feed on the rotting meat. The meat itself did not spontaneously generate the maggots.



Albert_Edelfelt_-_Louis_Pasteur_-_1885.jpg Photo from Wikimedia Commons

To put Pasteur’s experiment into the above terms, the shape of the flask’s neck was the independent variable and the amount of bacterial growing in each flask was the dependent variable that Pasteur tested for. The open-neck flask was the control group used to compare the swan-neck flask that was used for the treatment group.

Wikimedia commons L0057281 Copy of Pasteur's flask used in his experiments on spontaneous generation Credit: Science Museum, London. Wellcome Images images@wellcome.ac.uk http://wellcomeimages.orgCopy_of_Pas...e_L0057281.jpg



Erlenmyer flask By Hannes Grobe 19:04, 3 September 2006 (UTC) - Own work, CC BY-SA 2.5,https://commons.wikimedia.org/w/index.php

The above is an example of a **manipulative experiment** in which a single variable is to be changed under controlled conditions. Many people think that manipulative experiments are the only way in which science is done, but there are many cases in which the phenomena being studied are too big or too distant in space or time to be studied by a controlled experiment in the lab. In these cases, scientists learn by doing **observational science**. For example, we cannot build a star in a lab and study it up close. Fortunately, our galaxy is filled with billions of stars of different sizes, ages, and temperatures. By collecting data from many stars in various stages of stellar evolution, astronomers can build a model for how stars form and change over time. Astronomy is, therefore, largely an observational science.

A scientific experiment must be repeatable, that is, you or someone else conducting the same study should get similar results. One case might be a fluke, but if several repeats of the experiment yield similar results, then the hypothesis is better supported.

Once the scientist has completed their study, the usual practice is for them to write a paper and submit it to a peer-reviewed journal. Peer review is the process by which scientists in the same field evaluate each other's work. When a journal receives a proposed paper, it sends it out to several other scientists (the "peers") who review it and recommend whether to publish it. If the peers conclude that the research followed good scientific methodology and the data support the conclusions, they recommend publication. Otherwise, the paper is rejected, and the scientist has to do more work before resubmitting.

Unfortunately, there are many places where "scientific" papers can be published without peer review. Many of these are pay-for-publishing journals that will publish almost any paper if the researcher pays a fee. Also, some organizations with a political agenda may self-publish what looks like legitimate research that is slanted to reach a predetermined conclusion.

Today, few people dispute the fact that there is a strong link between smoking tobacco and certain forms of cancer. However, for decades, doubt was sown by an organization called the Tobacco Institute, which published many convincing-looking papers. All these papers came to the same conclusion: "Gosh, we just can't find any link between tobacco and cancer." This was the opposite of what nearly every other researcher in the field concluded. However, to be able to come to different results? Well, the Tobacco Institute was funded by the tobacco industry, and we now know that they were under orders by their sponsors to come to predetermined conclusions no matter what the data said.

More recently, a research paper in a pay-to-publish journal created a sensation in the news media by announcing that you can lose weight by eating chocolate. Wouldn't that be great? Sounds too good to be true, right? Well, it was. The researcher behind it came forward to admit that the entire paper was a hoax. He did it to highlight how easy it is to get bogus studies published and how readily the media can hype what seem like sensational results. Sadly, most journalists are not trained to discern the difference between sound science and what we can label **"junk science"** or **pseudoscience**.

Science plays a big role in our understanding of the world around us. It is, therefore, imperative that we have a scientifically literate society that is capable of discerning good science from junk science, especially when making decisions relating to their health and well-being.

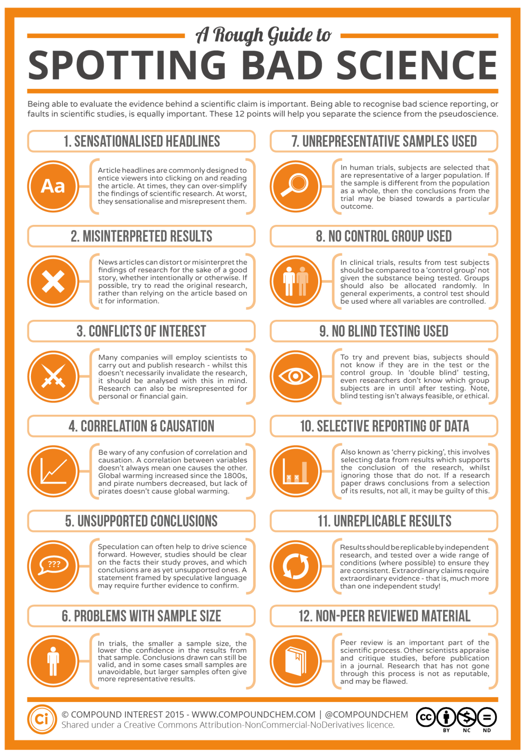
One final word on science and relates to how people use the word **theory**. Many non-scientists use the word to mean a guess or a hunch based on incomplete information. However, this is now how scientists use the term. In science, a theory is a broad explanation for a phenomenon that has been well-tested, shown to be supported repeatedly by experiments, and has gained wide acceptance. It is not a single hunch or guess. The way non-scientists use the term theory is more akin to how scientists use the word hypothesis. Another misconception is that if a hypothesis is validated by experiment, it may be “promoted” to become a theory. That is not accurate either. A **theory** is a broader explanation, while a hypothesis is generally narrower in scope. Indeed, a single theory may encompass several hypotheses. A theory offers a deeper, more detailed explanation for why things happen as they do in nature, like Einstein's Theory of Relativity explaining gravity through the curvature of space-time. It’s not just an isolated observation; it's a comprehensive model that explains a wide range of phenomena.

On the other hand, a law describes what happens based on consistent observational data, such as Newton's Laws of Motion that describe how objects move but do not explain why they move that way. Laws provide a description of an observed phenomenon without looking into the mechanics behind it. They are universally accepted as true under consistent conditions and help predict outcomes.

It’s important to note that in science, a hypothesis does not simply "evolve" into a theory through validation. A theory is a broader and more complex explanation that often encompasses several hypotheses. The transition from hypothesis to theory involves a significant accumulation of evidence and broader acceptance in the scientific community.

Keep that in mind when someone dismisses a scientific principle as “just a theory.” Nearly everything you are taught in a science class is based on theory. Of course, just because a theory has gained broad acceptance does not always mean it is true, but it takes a lot of evidence to overturn a theory that has been repeatedly validated by observation. Thus, much of what you learn in science classes is based on theories—well-established, widely tested, and crucial for advancing our understanding of the natural world.

Evaluating Science in the Media



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