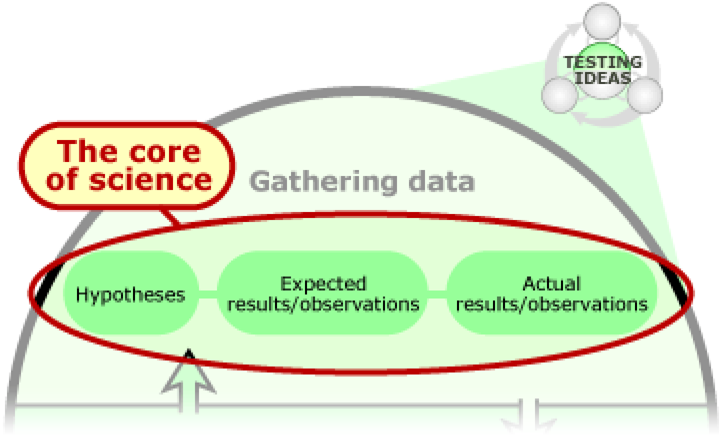
The core of science: Relating evidence and ideas



In *What is science?* and *How science works*, we've seen that science and scientists are diverse. From distant galaxies to the tiniest particles of matter, from the beginnings of time to next year's hurricane season, from the interactions of global economies to the chemical reactions within a single neuron, science investigates all natural phenomena. And scientists approach these investigations in all sorts of ways. Some depend on experiments, some on observational studies. Some lead to dead ends, some to unexpected discoveries. Some result in a technological advance, and some cast doubt on an established theory. But despite all that diversity, the aim of science remains unchanged—to build more accurate and powerful natural explanations of how the universe works—and *that* requires testing ideas with evidence to build scientific arguments. These arguments form the core of science.

Building a scientific argument:

Idea | Expectations | Actual observations

In this case, the term argument refers not to a disagreement between two people, but to an evidence-based line of reasoning—so scientific arguments are more like the closing argument in a court case (a logical description of what we think and why we think it) than they are like the fights you may have had with siblings. Scientific arguments involve three components: the idea (a hypothesis or theory), the expectations generated by that idea (frequently called predictions), and the actual observations relevant to those expectations (the evidence). These components are always related in the same logical way:

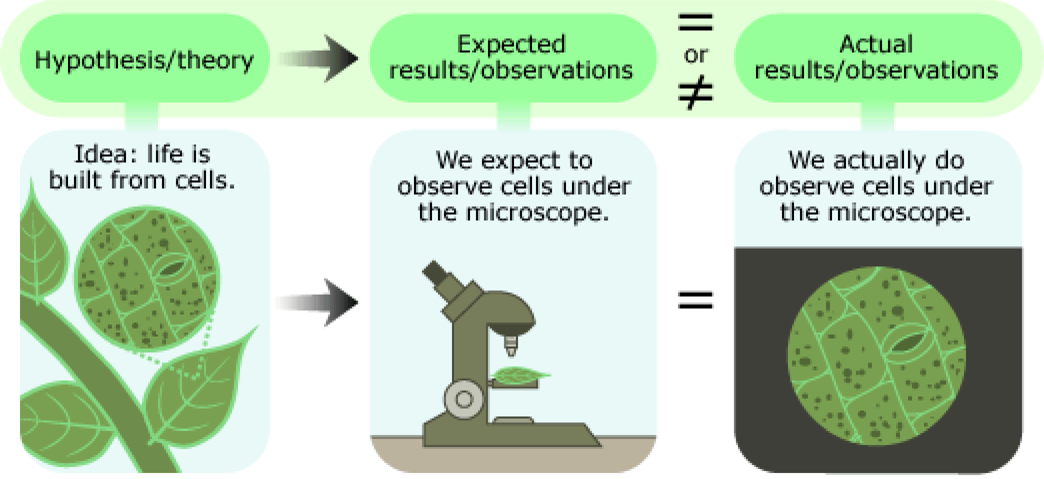
1. **What would we expect to see if this idea were true (i.e., what is our expected observation)?**
2. **What do we actually observe?**
3. **Do our expectations match our observations?**

PREDICTIONS OR EXPECTATIONS?

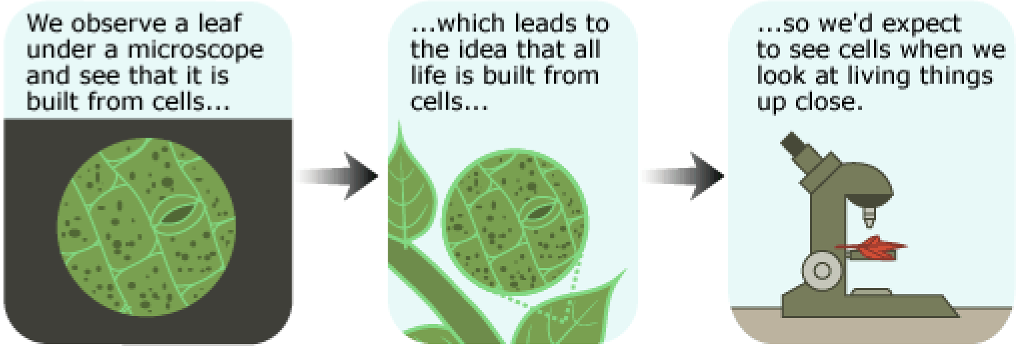
When scientists describe their arguments, they frequently talk about their expectations in terms of what a hypothesis or theory predicts: “If it were the case that smoking causes lung cancer, then we’d *predict* that countries with higher rates of smoking would have higher rates of lung cancer.” At first, it might seem confusing to talk about a prediction that doesn’t deal with the future, but that refers to something going on right now or that may have already happened. In fact, this is just another way of discussing the expectations that the hypothesis or theory generates. So when a scientist talks about the predicted rates of lung cancer, he or she really means something like “the rates that we’d expect to see if our hypothesis were correct.”

If the idea generates expectations that hold true (are actually observed), then the idea is more likely to be accurate. If the idea generates expectations that don’t hold true (are not observed), then we are less likely to accept the idea. For example, consider the idea that cells are the building blocks of life. If that idea were true, we’d expect to see cells in all kinds of living tissues observed under a microscope—that’s our expected observation. In fact, we do observe this (our actual observation), so evidence supports the idea that living things are built from cells.

The logic of the argument:

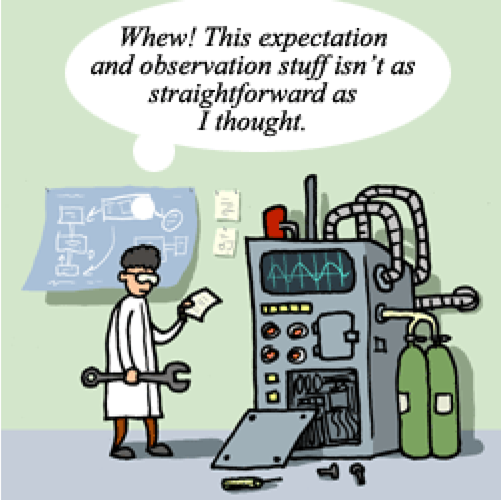


How the argument is actually assembled:



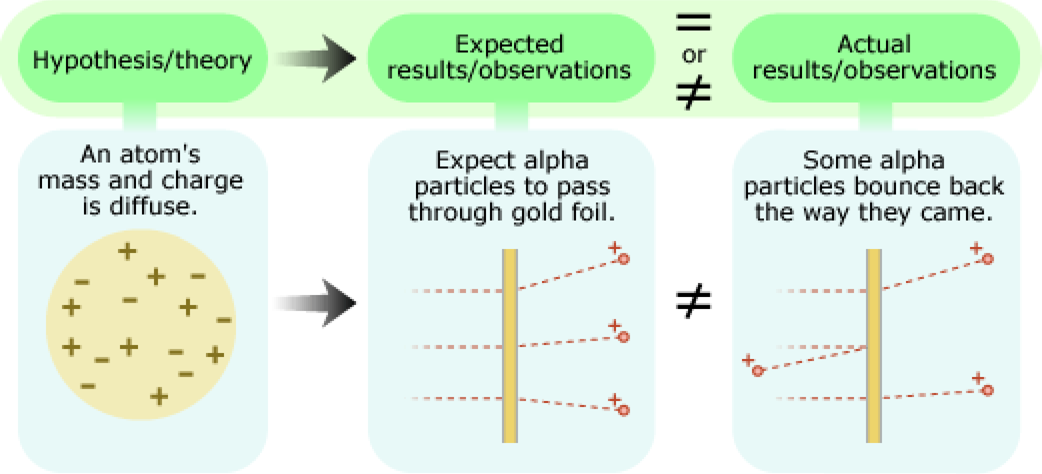
Though the structure of this argument is consistent (hypothesis, then expectation, then actual observation), its pieces may be assembled in different orders. For example, the first observations of cells were made in the 1600s, but cell theory was not postulated until 200 years later—so in this case, the evidence actually helped inspire the idea. Whether the idea comes first or the evidence comes first, the logic relating them remains the same.

Putting the pieces together: The hard work of building arguments

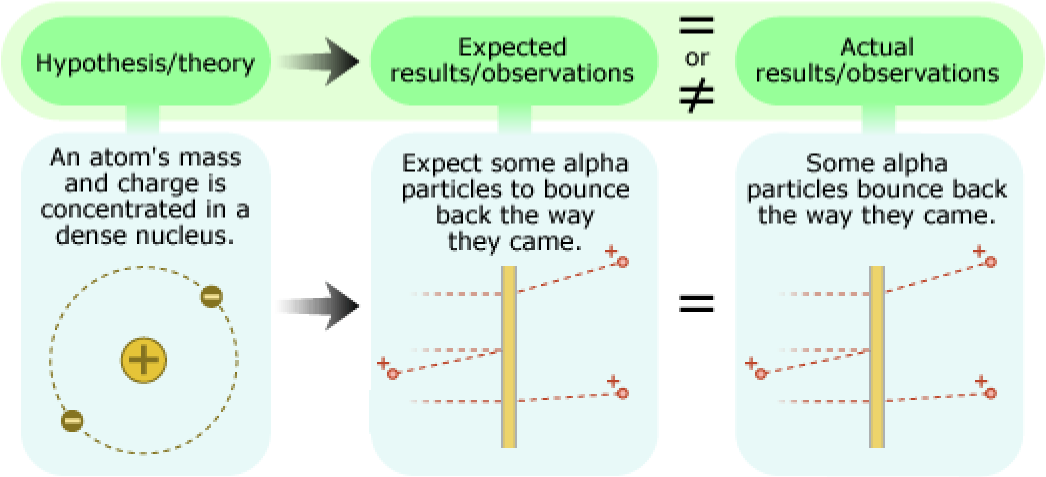


Though the structure of a scientific argument may seem straightforward—a hypothesis generates expectations which then may or may not be observed—assembling those pieces may take a lot of work. Substantial analysis and background knowledge are often involved in figuring out what expectations are generated by a particular hypothesis or theory. And it might take even more work (e.g., the development of a new tool, like a Geiger counter) and time (e.g., waiting for the next magnitude 6.0 earthquake) to gather the observations relevant to an idea.

For example, consider the hypothesis that an atom's mass and positive charge are spread diffusely throughout the atom. The idea is simple enough, but unless you happen to know a lot about particle physics and electromagnetism, the expectations that it generates are not immediately obvious. Those bodies of knowledge suggest that if this idea were true, then tiny, positively charged alpha particles should be able to pass right through a gold atom without much deflection. Again, this expectation sounds simple enough, but actually setting up the experiment to validate it is tough: you need a means of producing alpha particles, a way to shoot them through gold foil, and a method for detecting their deflection. Only then would you be able to get the observations relevant to your hypothesis. In the early 1900s, Ernest Rutherford and his colleagues performed this experiment and found that their expectations and actual observations did not match at all: some of the alpha particles came bouncing back the way they came, as though they'd bumped into something solid!



The results did not support the diffuse mass hypothesis. However, they did suggest another hypothesis to Rutherford—that atoms have a dense, positively-charged nucleus—and helped him construct a new scientific argument:

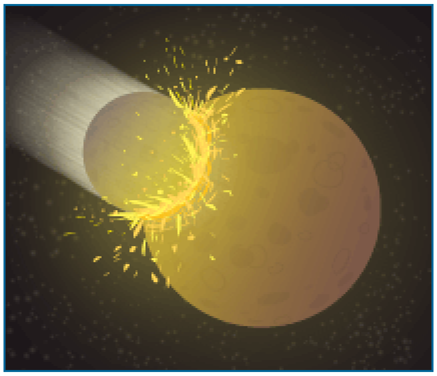


Rutherford's tests aimed to reveal the inner structure of atoms—entities that surround us all the time. But scientific tests also allow us to learn about entities like the dinosaurs or the atoms produced by the Big Bang, which no longer exist today …

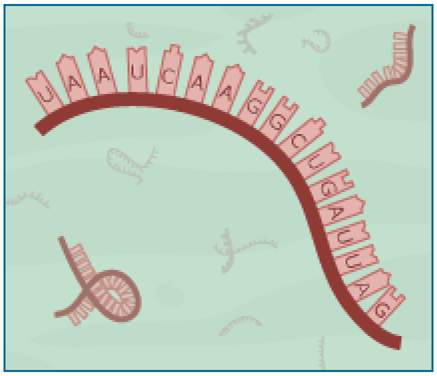
Predicting the past

Scientific arguments work the same way—whether we are interested in an ongoing phenomenon (say, gravity) or ancient history (say, the origin of life). It might at first seem strange to generate expectations about something that happened long ago, but in fact, it's no different than generating expectations based on any other hypothesis or theory. The key is to remember that we are figuring out what we would *expect to observe today*, if a particular event had happened in the past.

These examples illustrate how scientific ideas about past events can generate testable expectations:



- **Idea: The moon chipped off the old block**—that is, the moon formed from debris flung up by early Earth when it was struck by another large body. This proposed event would have happened some 4.5 billion years ago; nevertheless, a little reasoning and some background knowledge easily lets us generate expectations to test this idea. For example, if the chip-off-the-old block theory were true, the moon should have a similar composition to that of the Earth's crust 4.5 billion years ago. Well-established ideas in geology and planetary science suggest that, by that time, iron and heavy elements in Earth's crust would have already sunk to its core. So we would expect the moon to be deficient in iron like the Earth's crust, and in fact, recent Apollo missions have borne out this expectation. Moon rocks are low in iron, which lends support to the chip-off-the-old-block theory.



- **Idea: It was an RNA world**—that is, RNA arose several billion years ago as the first self-replicating molecule and formed the basis of heredity and metabolism in the ancestor of all life on Earth. What expectations can we generate about such ancient chemical reactions? Well, if the idea were accurate, then we would expect to be able to recreate some of the key chemical reactions leading up to replicating RNA. After all, if a particular chemical reaction actually happened on early Earth, then we should be able to produce a similar reaction in a lab situation that simulates conditions on early Earth. Has this expectation been borne out and thus, lent support to the theory? To some extent, but science is a work in progress. Many plausible chemical reactions in this sequence have been discovered, but there are still gaps in our knowledge, which are being filled as chemists continue to work on this knotty problem.

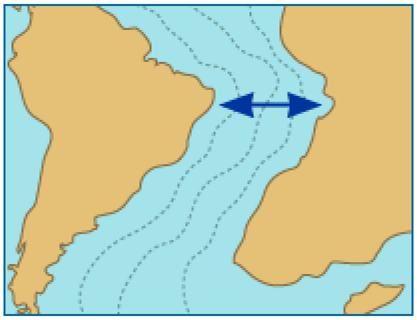
- **Idea: Once, there were no borders**—that is, some 250 million years ago, all the continents we know today were joined together like a jigsaw puzzle. How can we know where the continents *used* to be? Well, from the clues they left behind, of course. If the continents had been joined together, then the ancient animals that lived on them should have roamed freely across what are now continental coastlines. Thus, where fossilization was likely, we would expect to find corresponding fossils on the coasts of now distant continents. And in fact we do observe this. For example, fossils of the extinct reptile *Cynognathus* dating to around 240 million years ago have been found in both South Africa and South America, lending support to the no-borders idea.

Here we've examined just one expectation (and one line of evidence) generated by each of three scientific ideas, but of course, in reality, each of these ideas generates *multiple* expectations …

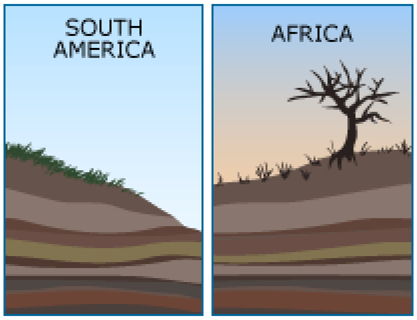
Arguments with legs to stand on

Powerful scientific ideas generate many different expectations, not just one. As an example, let's return to the idea that the continents as we know them today were once joined together into a supercontinent and have been moving apart ever since. This idea generates many different expectations; we would expect to find:

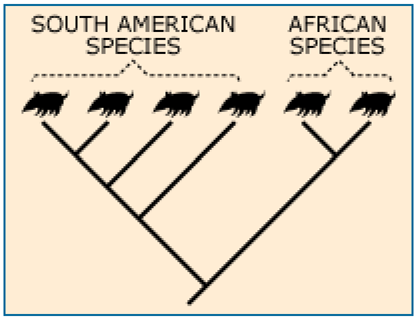
Corresponding fossils on now distant continents.



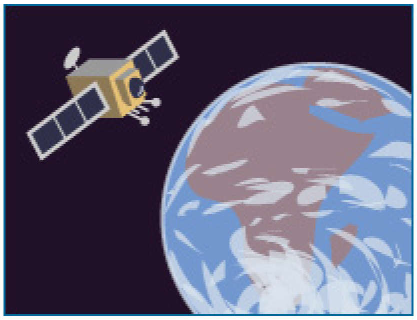
That the continents are shaped in ways that could have once fit together.



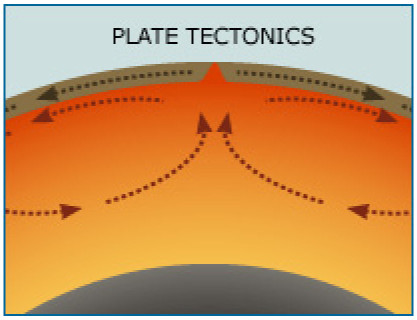
That rock layers and geological features on now distant continents match up where they were once joined.



That the evolutionary relationships among non-marine species reflect the ancient supercontinental break up.



Direct evidence of ongoing tectonic movement through sensitive satellite measurements.



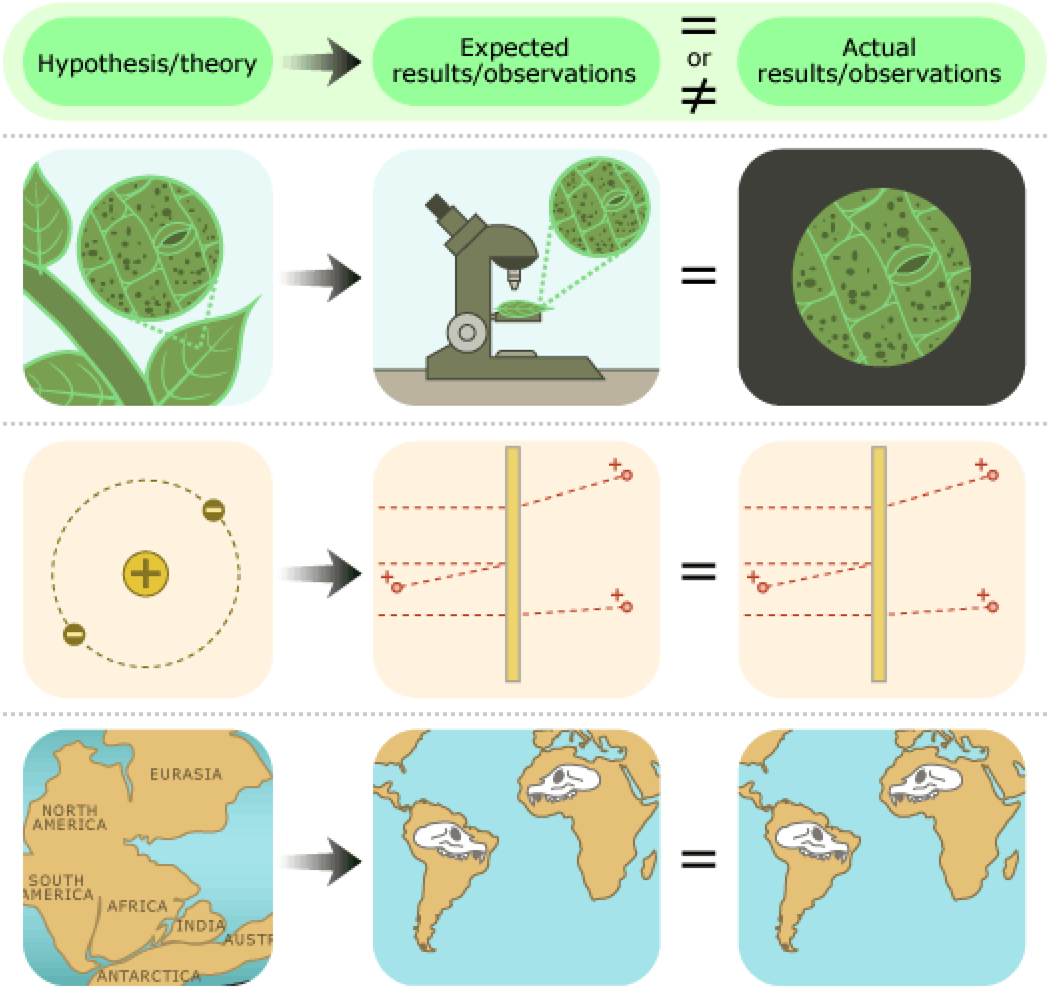
A plausible mechanism by which the continents could have moved.

From ancient fossils to cutting-edge satellite measurements, the expectations generated by this idea have all been borne out in actual observations. Such diverse observations all pointing to a single idea (in this case, plate tectonics) provide that idea with robust support that can withstand the prodding and scrutiny of science—like a table built on many legs, instead of a couple wobbly ones.

So one hypothesis or theory is often related to many different sorts of expected observations—all of which reflect on its accuracy. It's no wonder then that evaluating scientific ideas is not cut and dried: some expectations generated by an idea might be borne out and support it, while others might not.

Summing up scientific arguments

In this section, we've seen that scientific arguments are formed by figuring out what we would expect to observe if a particular idea were true and then checking those expectations against what we actually observe. A match between expectations and observations lends support to the idea, while a mismatch helps refute the idea. That is the simple, but powerful, core of a scientific argument. This core applies across the board, whether we are investigating broad theories or minute hypotheses, whether we are investigating mechanisms so small we can't observe them with a microscope, so distant we can't see them with a telescope, so far in the past that no human was there to observe them, or so commonplace that they must be at work every time an object falls to the ground. While scientific disciplines vary in their focus of study, they all take this same approach to forming scientific arguments.



Scientific arguments are built through interactions within the scientific community. To learn more about the community's role in science, read on …