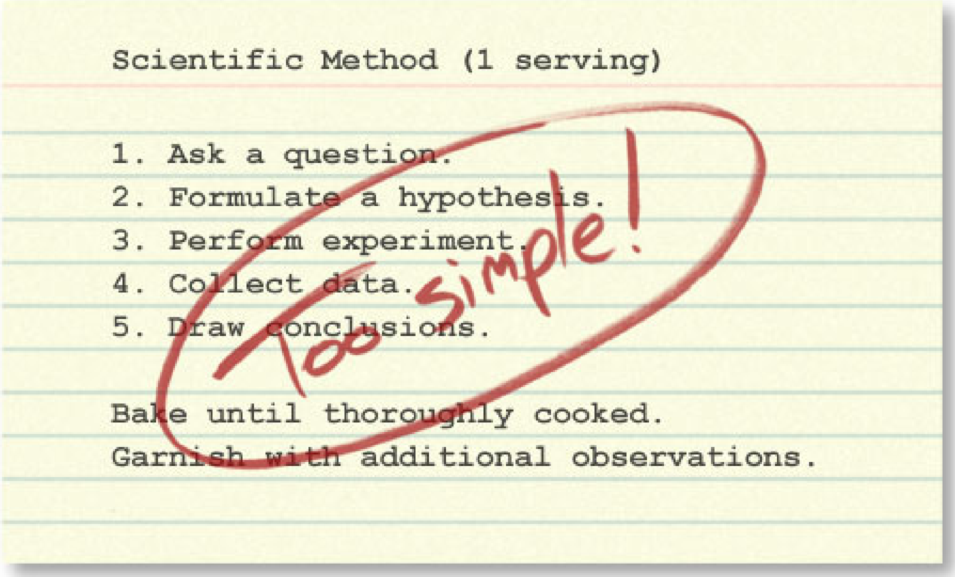
How science works

The Scientific Method is traditionally presented in the first chapter of science textbooks as a simple recipe for performing scientific investigations. Though many useful points are embodied in this method, it can easily be misinterpreted as linear and "cookbook": pull a problem off the shelf, throw in an observation, mix in a few questions, sprinkle on a hypothesis, put the whole mixture into a 350° experiment—and *voila*, 50 minutes later you'll be pulling a conclusion out of the oven! That might work if science were like Hamburger Helper®, but science is complex and cannot be reduced to a single, prepackaged recipe.



Scientific Method (1 serving)

1. Ask a question.
2. Formulate a hypothesis.
3. Perform experiment.
4. Collect data.
5. Draw conclusions.

Bake until thoroughly cooked.
Garnish with additional observations.

Too simple!

The linear, stepwise representation of the process of science is simplified, but it does get at least one thing right. It captures the core logic of science: testing ideas with evidence. However, this version of the scientific method is so simplified and rigid that it fails to accurately portray how real science works. It more accurately describes how science is summarized *after the fact*—in textbooks and journal articles—than how science is actually done.

The simplified, linear scientific method implies that scientific studies follow an unvarying, linear recipe.

But in reality, in their work, scientists engage in many different activities in many different sequences. Scientific investigations often involve repeating the same steps many times to account for new information and ideas.

The simplified, linear scientific method implies that science is done by individual scientists working through these steps in isolation.

But in reality, science depends on interactions within the scientific community. Different parts of the process of science may be carried out by different people at different times.

The simplified, linear scientific method implies that science has little room for creativity.

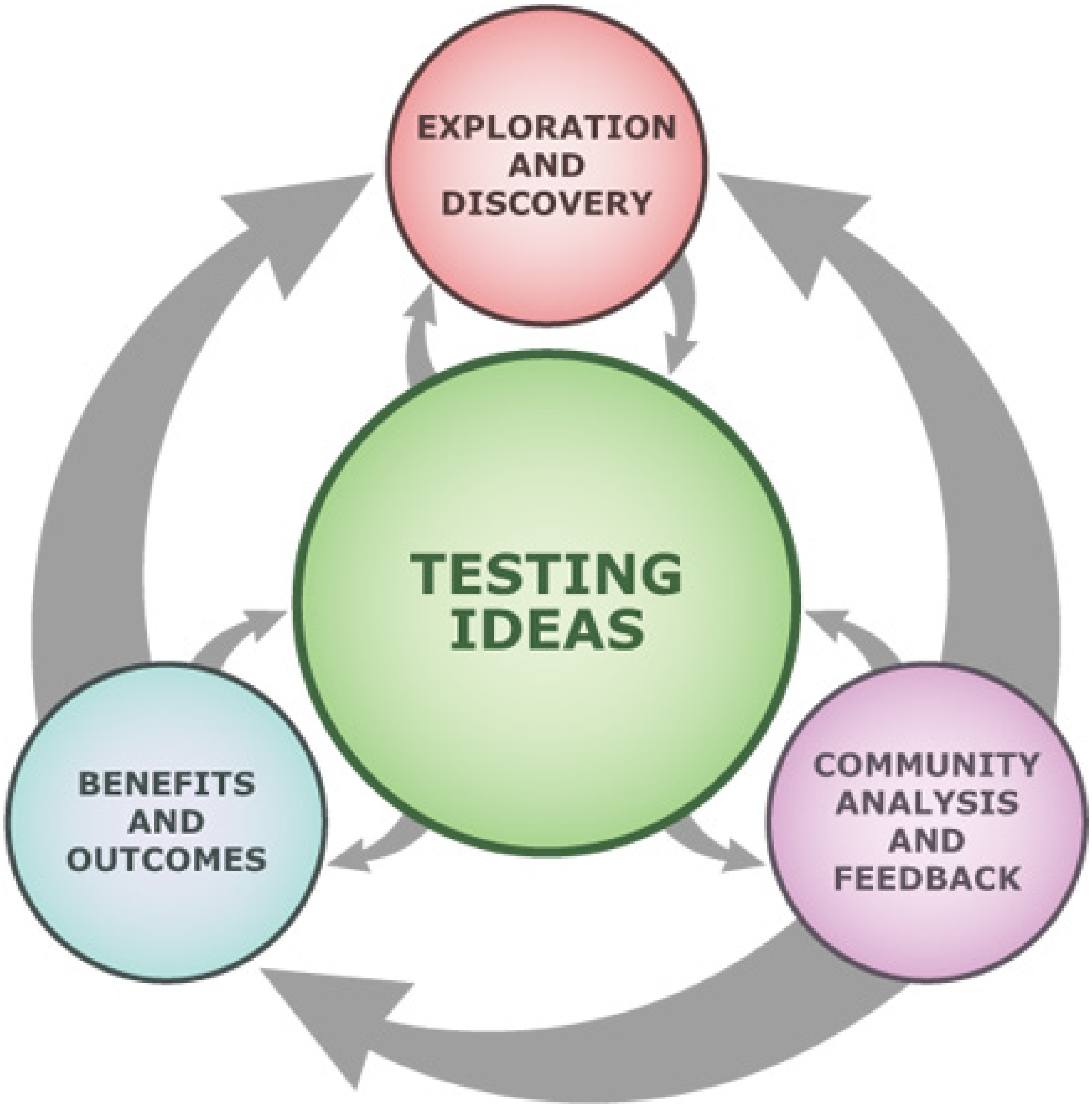
But in reality, the process of science is exciting, dynamic, and unpredictable. Science relies on creative people thinking outside the box!

The simplified, linear scientific method implies that science concludes.

But in reality, scientific conclusions are always revisable if warranted by the evidence. Scientific investigations are often ongoing, raising new questions even as old ones are answered.

The real process of science

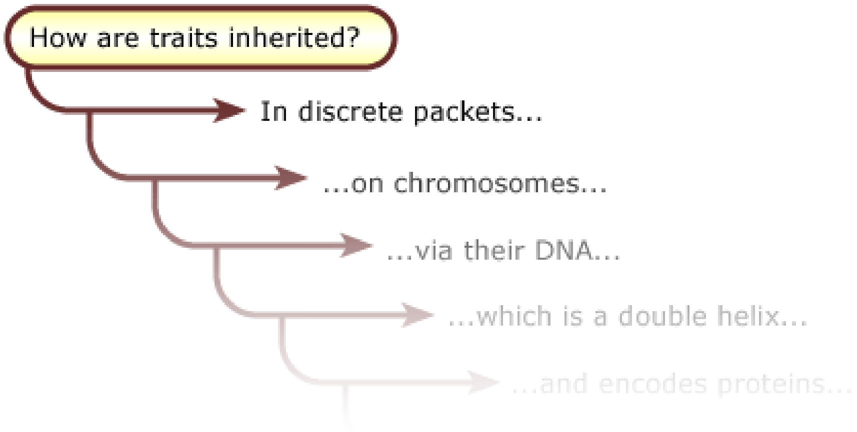
The process of science, as represented here, is the opposite of "cookbook" (to see the full complexity of the process, roll your mouse over each element). In contrast to the linear steps of the simplified scientific method, this process is non-linear:



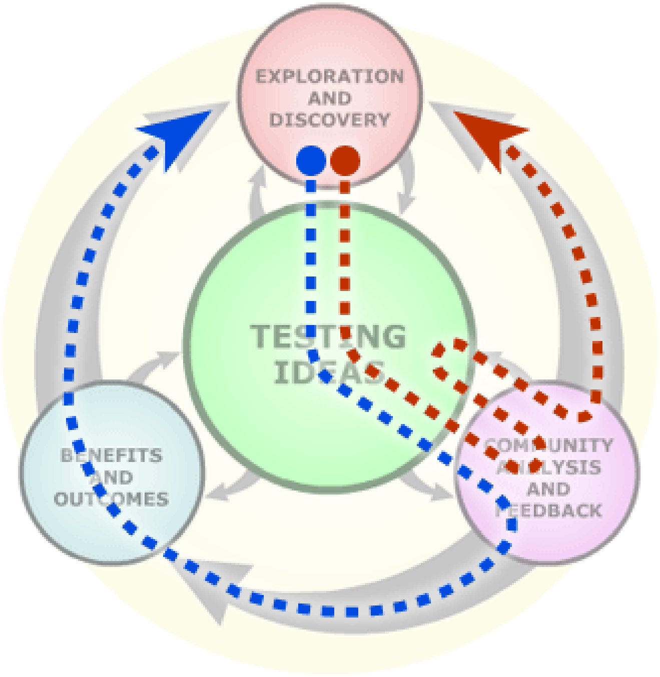
- **The process of science is iterative.**
  Science circles back on itself so that useful ideas are built upon and used to learn even more about the natural world. This often means that successive investigations of a topic lead back to the same question, but at deeper and deeper levels. Let's begin with the basic question of how biological inheritance works. In the mid-1800s, Gregor Mendel showed that inheritance is particulate—that information is passed along in discrete packets that cannot be diluted. In the early 1900s, Walter Sutton and Theodor Boveri (among others) helped show that those particles of inheritance, today known as genes, were located on chromosomes. Experiments by Frederick Griffith, Oswald Avery, and many others soon elaborated on this understanding by showing that it was the DNA in chromosomes which carries genetic information. And then in 1953, James Watson and Francis Crick, again aided by the work of many others, provided an even more detailed understanding of inheritance by outlining the molecular structure of DNA. Still later in the 1960s, Marshall Nirenberg, Heinrich Matthaei, and others built upon this work to unravel

the molecular code that allows DNA to encode proteins. And it doesn't stop there. Biologists have continued to deepen and extend our understanding of genes, how they are controlled, how patterns of control themselves are inherited, and how they produce the physical traits that pass from generation to generation.

Science investigates questions at deeper and deeper levels:



- **The process of science is not predetermined.**
  Any point in the process leads to many possible next steps, and where that next step leads could be a surprise. For example, instead of leading to a conclusion about tectonic movement, testing an idea about plate tectonics could lead to an observation of an unexpected rock layer. And that rock layer could trigger an interest in marine extinctions, which could spark a question about the dinosaur extinction—which might take the investigator off in an entirely new direction.

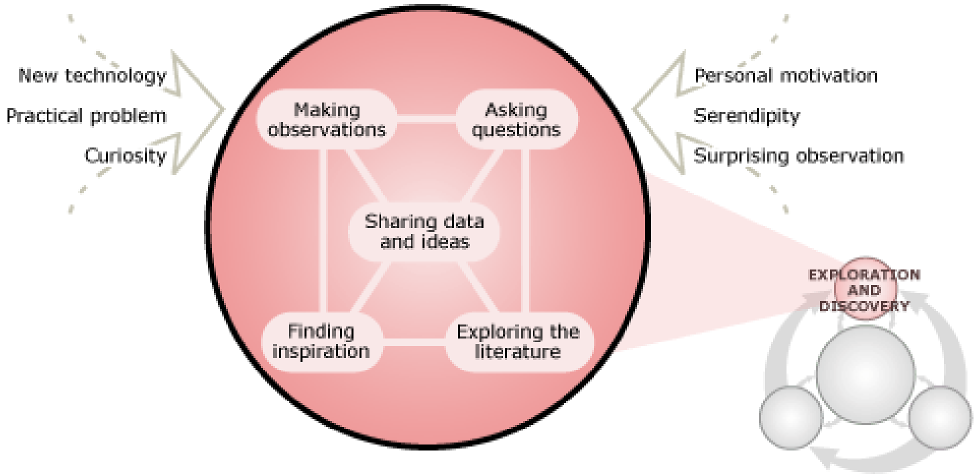


At first this process might seem overwhelming. Even within the scope of a single investigation, science may involve many different people engaged in all sorts of different activities in different orders and at different points in time—it is simply much more dynamic, flexible, unpredictable, and rich than many textbooks represent it as. But don't panic! The scientific process may be complex, but the details are less important than the big picture …

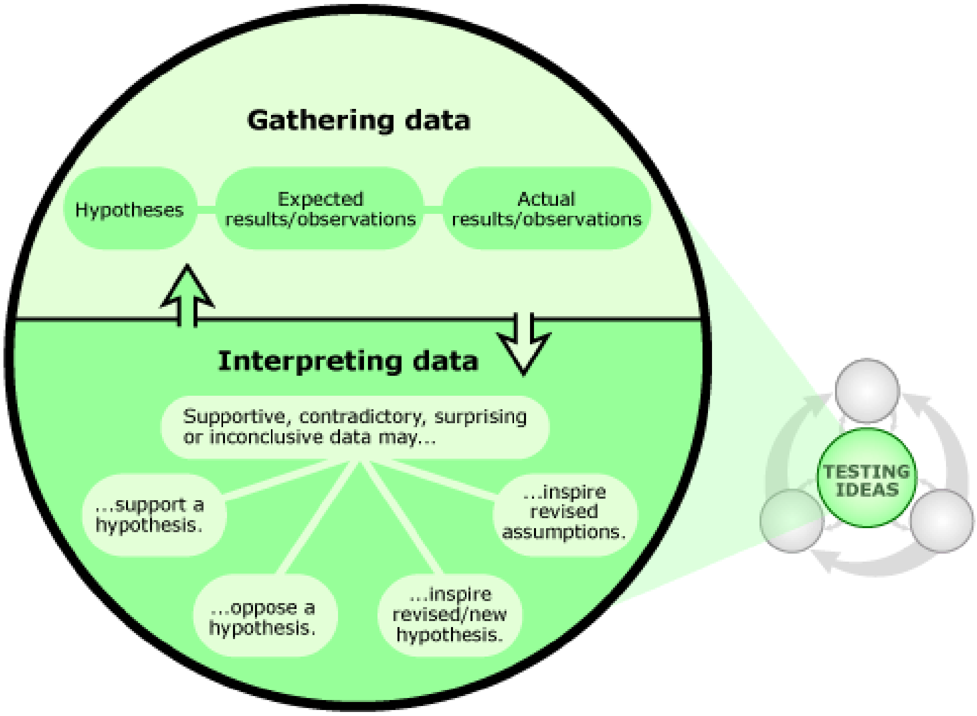
A blueprint for scientific investigations

The process of science involves many layers of complexity, but the key points of that process are straightforward:

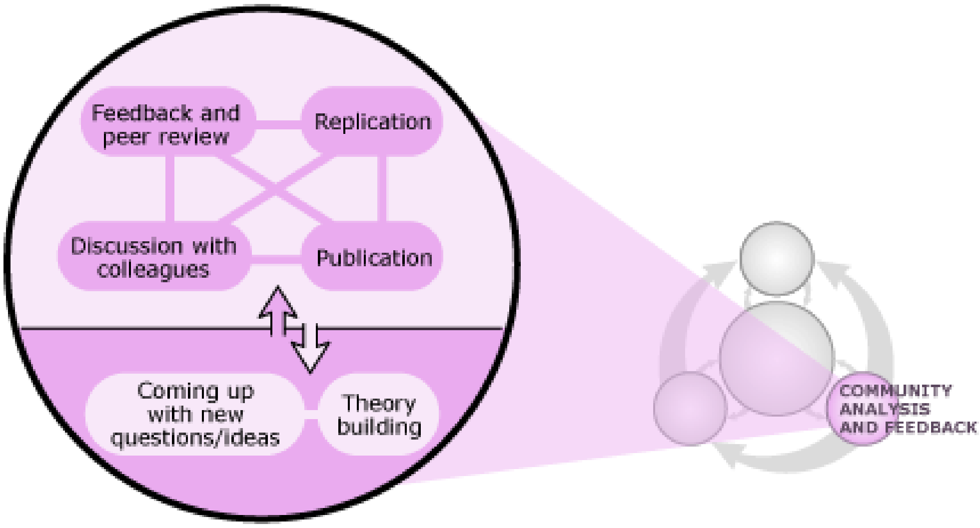
There are many routes into the process—from serendipity (e.g., being hit on the head by the proverbial apple), to concern over a practical problem (e.g., finding a new treatment for diabetes), to a technological development (e.g., the launch of a more advanced telescope)—and scientists often begin an investigation by plain old poking around: tinkering, brainstorming, trying to make some new observations, chatting with colleagues about an idea, or doing some reading.



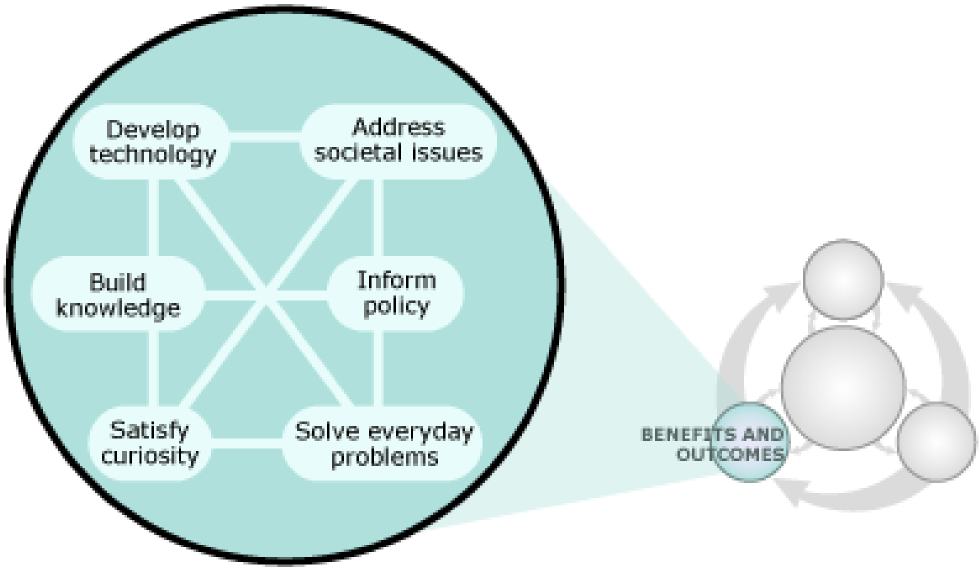
Scientific testing is at the heart of the process. In science, all ideas are tested with evidence from the natural world, which may take many different forms—from Antarctic ice cores, to particle accelerator experiments, to detailed descriptions of sedimentary rock layers. You can't move through the process of science without examining how that evidence reflects on your ideas about how the world works—even if that means giving up a favorite hypothesis.



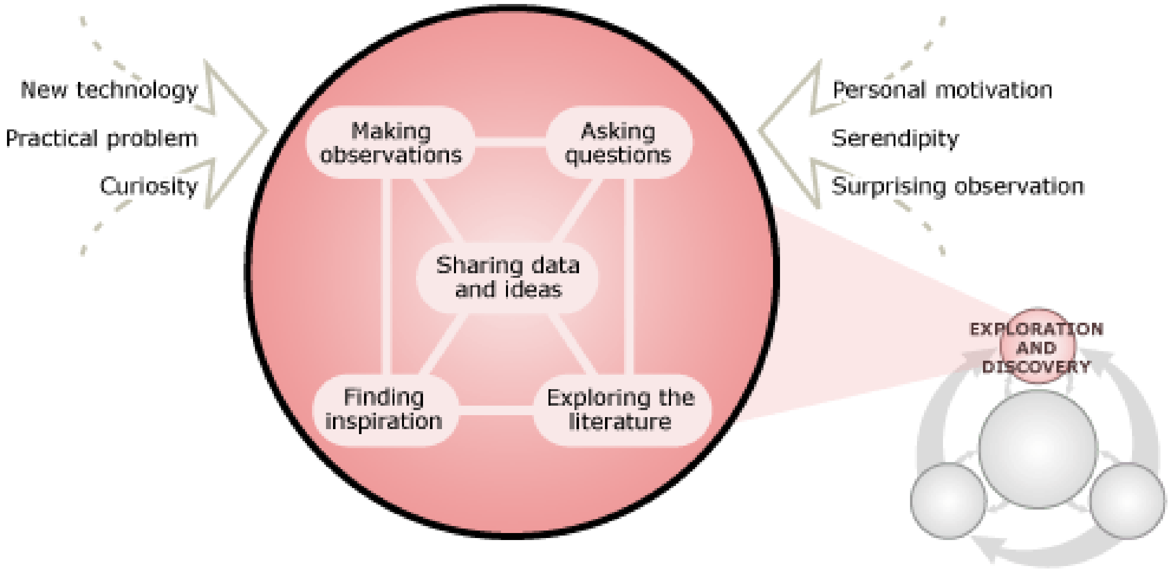
The scientific community helps ensure science's accuracy. Members of the scientific community (i.e., researchers, technicians, educators, and students, to name a few) play many roles in the process of science, but are especially important in generating ideas, scrutinizing ideas, and weighing the evidence for and against them. Through the action of this community, science is self-correcting. For example, in the 1990s, John Christy and Roy Spencer reported that temperature measurements taken by satellite, instead of from the Earth's surface, seemed to indicate that the Earth was cooling, not warming. However, other researchers soon pointed out that those measurements didn't correct for the fact that satellites slowly lose altitude as they orbit and that once these corrections are made, the satellite measurements were much more consistent with the warming trend observed at the surface. Christy and Spencer immediately acknowledged the need for that correction.



The process of science is intertwined with society. The process of science both influences society (e.g., investigations of X-rays leading to the development of CT scanners) and is influenced by society (e.g., a society's concern about the spread of HIV leading to studies of the molecular interactions within the immune system).



Exploration and discovery



The early stages of a scientific investigation often rely on making observations, asking questions, and initial experimentation—essentially poking around—but the routes to and from these stages are diverse. Intriguing observations sometimes arise in surprising ways, as in the discovery of radioactivity, which was inspired by the observation that photographic plates (an early version of camera film) stored next to uranium salts were unexpectedly exposed. Sometimes interesting observations (and the investigations that follow) are suddenly made possible by the development of a new technology. For example, the launch of the Hubble Space Telescope in 1990 allowed astronomers to make deeper and more focused observations of our universe than were ever before possible. These observations ultimately led to breakthroughs in areas as diverse as star and planet formation, the nature of black holes, and the expansion of the universe.

Observations like this image from the Hubble Telescope can lead to further breakthroughs.

Sometimes, observations are clarified and questions arise through discussions with colleagues and reading the work of other scientists—as demonstrated by the discovery of the role of chlorofluorocarbons (CFCs) in ozone depletion …

Hubble image provided by NASA, ESA, and A. Nota (STScI/ESA)

EXPLORING AEROSOLS

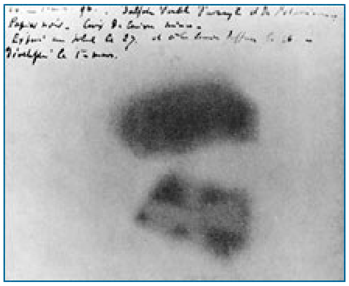
Mario Molina

In 1973, chemists had observed that CFCs were being released into the environment from aerosol cans, air conditioners, and other sources, but it was discussions with his colleague and advisor, Sherwood Rowland, that led Mario Molina to ask what their ultimate fate was. Since CFCs were rapidly accumulating in the atmosphere, the question was intriguing, but before he could tackle the issue (which would ultimately lead to a Nobel Prize and an explanation for the hole in the ozone layer), Molina needed more information. He had to learn more about other scientists' studies of atmospheric chemistry, and what he learned pointed to the disturbing fate of CFCs.

Furthermore, though observation and questioning are essential to the process of science, on their own, they are not enough to launch a scientific investigation; generally, scientists also need scientific background knowledge—all the information and understandings they've picked up from their scientific training in school, supplemented by discussions with colleagues and reviews of the scientific literature. As in Mario Molina's story, an understanding of what other scientists have already figured out about a particular topic is critical to the process. This background knowledge allows scientists to recognize revealing observations for what they are, to make connections between ideas and observations, and to figure out which questions can be fruitfully tackled with available tools. The importance of content knowledge to the process of science helps explain why science is often mischaracterized as a static set of facts contained in textbooks—science *is* a process, but one that relies on accumulated knowledge to move forward.

THE SCIENTIFIC STATE OF MIND

Henri Becquerel



The ruined photo plate that got Becquerel thinking

Some scientific discoveries are chalked up to the serendipity of being in the right place at the right time to make a key observation—but rarely does serendipity alone lead to a new discovery. The people who turn lucky breaks into breakthroughs are generally those with the background knowledge and scientific ways of thinking needed to make sense of the lucky observation. For example, in 1896, Henri Becquerel made a surprising observation. He found that photographic plates stored next to uranium salts were spotted, as though they'd been exposed to light rays—even though they had been kept in a dark drawer. Someone else, with a less scientific state of mind and less background knowledge about physics, might have cursed their bad luck and thrown out the ruined plates. But Becquerel was intrigued by the observation. He recognized it as something scientifically interesting, went on to perform follow-up experiments that traced the source of the exposure to the uranium, and in the process, discovered radioactivity. The key to this story of discovery lies partly in Becquerel's instigating observation, but also in his way of thinking. Along with the relevant background knowledge, Becquerel had a scientific state of mind. Sure, he made some key observations — but then he dug into them further, inquiring *why* the plates were exposed and trying to eliminate different potential causes of the exposure to get to the physical explanation behind the happy accident.

Mario Molina photo by Donna Coveney/MIT

Observation beyond our eyes

We typically think of observations as having been seen "with our own eyes," but in science, observations can take many forms. Of course, we *can* make observations directly by seeing, feeling, hearing, and smelling, but we can also extend and refine our basic senses with tools: thermometers, microscopes, telescopes, radar, radiation sensors, X-ray crystallography, mass spectroscopy, etc. And these tools do a better job of observing than we can! Further, humans cannot directly sense many of the phenomena that science investigates (no amount of staring at this computer screen will ever let you see the atoms that make it up or the UV radiation that it emits), and in such cases, we must rely on indirect observations facilitated by tools. Through these tools, we can make many more observations much more precisely than those our basic senses are equipped to handle.

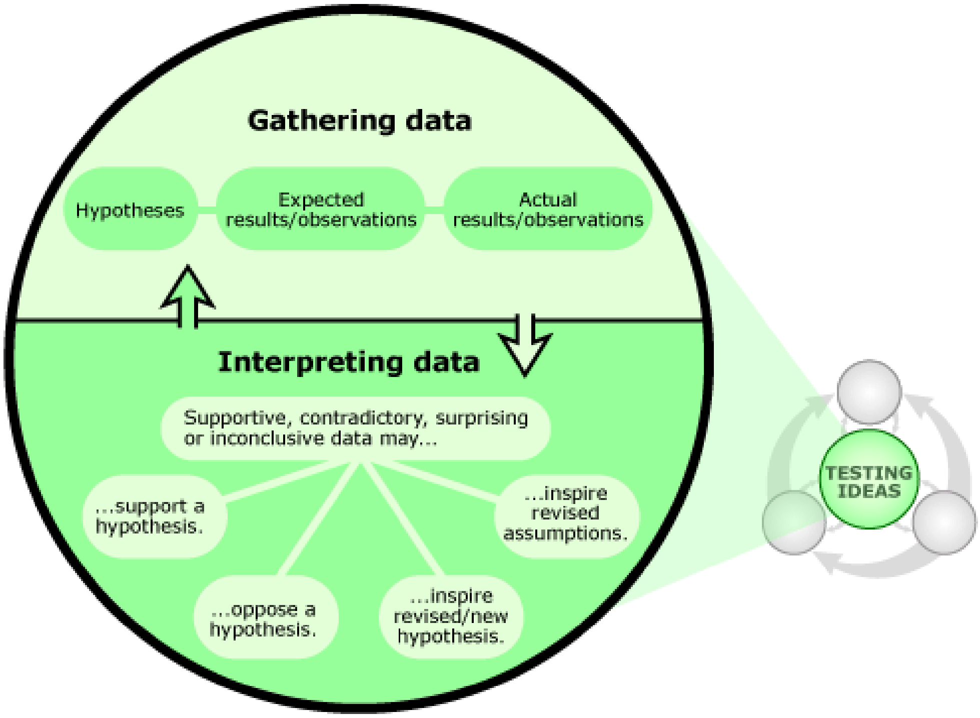
Tools like the Hubble Space Telescope, microscopes and submersibles help us to observe the natural world.

Observations yield what scientists call data. Whether the observation is an experimental result, radiation measurements taken from an orbiting satellite, an infrared recording of a volcanic eruption, or just noticing that a certain bird species always thumps the ground with its foot while foraging — they're all data. Scientists analyze and interpret data in order to figure out how those data inform their hypotheses and theories. Do they support one idea over others, help refute an idea, or suggest an entirely new explanation? Though data may seem complex and be represented by detailed graphs or complex statistical analyses, it's important to remember that, at the most basic level, they are simply observations.

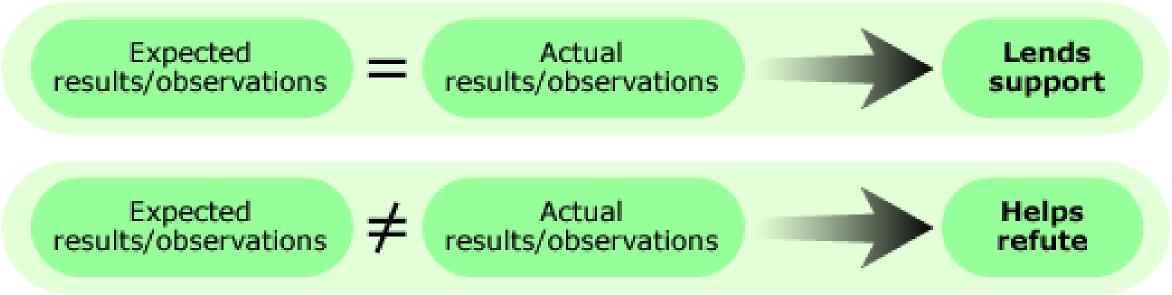
Observations inspire, lend support to, and help refute scientific hypotheses and theories. However, theories and hypotheses (the fundamental structures of scientific knowledge) cannot be directly read off of nature. A falling ball (no matter how detailed our observations of it may be) does not directly tell us how gravity works, and collecting observations of all the different finch species of the Galapagos Islands does not directly tell us how their beaks evolved. Scientific knowledge is built as people come up with hypotheses and theories, repeatedly test them against observations of the natural world, and continue to refine those explanations based on new ideas and observations. Observation is essential to the process of science, but it is only half the picture.

Hubble image provided by NASA; microscope photo from Scott Bauer/USDA; submersible photo from NOAA Ocean Explorer

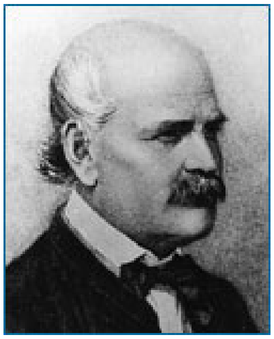
Testing scientific ideas



Testing hypotheses and theories is at the core of the process of science. Any aspect of the natural world *could* be explained in many different ways. It is the job of science to collect all those plausible explanations and to use scientific testing to filter through them, retaining ideas that are supported by the evidence and discarding the others. You can think of scientific testing as occurring in two logical steps: (1) if the idea is correct, what would we expect to see, and (2) does that expectation match what we actually observe? Ideas are supported when actual observations (i.e., results) match expected observations and are contradicted when they do not match.



TESTING IDEAS ABOUT CHILDBED FEVER


Ignaz Semmelweis

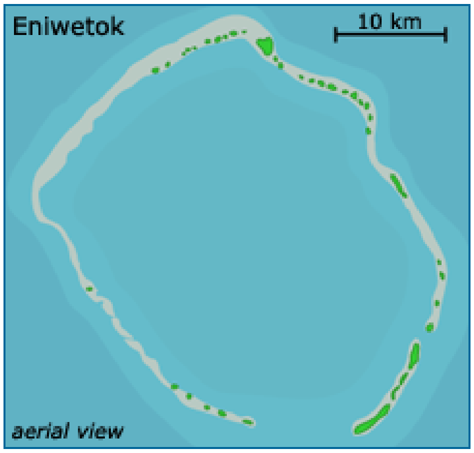
As a simple example of how scientific testing works, consider the case of Ignaz Semmelweis, who worked as a doctor on a maternity ward in the 1800s. In his ward, an unusually high percentage of new mothers died of what was then called childbed fever. Semmelweis considered many possible explanations for this high death rate. Two of the many ideas that he considered were (1) that the fever was caused by mothers giving birth lying on their backs (as opposed to on their sides) and (2) that the fever was caused by doctors' unclean hands (the doctors often performed autopsies immediately before examining women in labor).

He tested these ideas by considering what expectations each idea generated. If it were true that childbed fever were caused by giving birth on one's back, then changing procedures so that women labored on their sides should lead to lower rates of childbed fever. Semmelweis tried changing the position of labor, but the incidence of fever did not decrease; the actual observations did not match the expected results. If, however, childbed fever were caused by doctors' unclean hands, having doctors wash their hands thoroughly with a strong disinfecting agent before attending to women in labor should lead to lower rates of childbed fever. When Semmelweis tried this, rates of fever plummeted; the actual observations matched the expected results, supporting the second explanation.

Testing in the tropics


A coral atoll

Let's take a look at another, very different, example of scientific testing: investigating the origins of coral atolls in the tropics. Consider the atoll Eniwetok (Anewetak) in the Marshall Islands—an oceanic ring of exposed coral surrounding a central lagoon. From the 1800s up until today, scientists have been trying to learn what supports atoll structures beneath the water's surface and exactly how atolls form. Eniwetok could have formed in several ways:

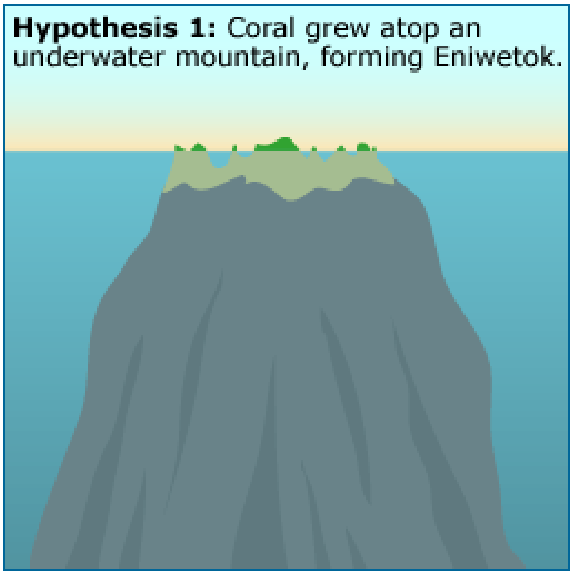


Hypothesis 1: Coral only grows near the surface of the ocean where light penetrates—so perhaps the coral that makes up Eniwetok grew in a ring atop an underwater mountain, which was itself built by oceanic debris or uplifted through tectonic action.

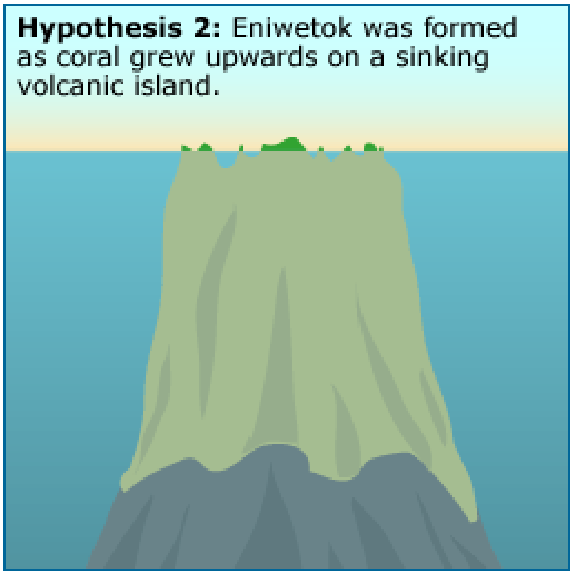
Hypothesis 2: Another possibility is that Eniwetok originally grew around a volcanic island, which then sunk beneath the surface of the water as the reef continued to grow to the surface. Underwater volcanic activity (i.e., hotspots) can produce an island in the middle of the ocean, as cooled lava builds up around the hotspot. However, tectonic plate movement eventually carries the island off the hotspot, keeping the island from being built up further. Meanwhile, coral organisms grow in a ring in the shallow waters surrounding the exposed volcanic island. As time passes, erosion and tectonic action cause the island to sink slowly (or subside), and as it does, it takes the coral ring with it. However, coral are living

Atoll photo from yunmeng's photostream on flickr (CC BY-NC-SA 2.0)

organisms and grow their colonies upwards as their substrate sinks. Over time, the island could sink deep below the surface of the water, while the coral continue to thrive, constantly growing towards the surface in their original ring configuration.



Hypothesis 1: Coral grew atop an underwater mountain, forming Eniwetok.



Hypothesis 2: Eniwetok was formed as coral grew upwards on a sinking volcanic island.

Which is a better explanation for Eniwetok? Is it built atop an underwater mountain, or is it a tower of coral growing atop an ancient sunken volcano? Which of these explanations is best supported by the evidence?

If Eniwetok grew atop an underwater mountain, then we would expect the atoll to be made up of a relatively thin layer of coral on top of limestone or basalt. But if it grew upwards around a subsiding island, then we would expect the atoll to be made up of many hundreds of feet of coral on top of volcanic rock. When geologists drilled into Eniwetok in 1951 as part of a survey preparing for nuclear weapons tests, the drill bored through more than 4000 feet (1219 meters) of coral before hitting volcanic basalt! The actual observation contradicted the underwater mountain explanation and matched the subsiding island explanation, supporting that idea. Of course, many other lines of evidence also shed light on the origins of coral atolls, but the surprising depth of coral on Eniwetok was particularly convincing to many geologists.

The logic of scientific arguments

Taken together, the expectations generated by a scientific idea and the actual observations relevant to those expectations form what we'll call a scientific argument. This is a bit like an argument in a court case—a logical description of what we think and why we think it. A scientific argument uses evidence to make a case for whether a scientific idea is accurate or inaccurate. For example, the idea that illness in new mothers can be caused by doctors' dirty hands generates the expectation that illness rates should go down when doctors are required to wash their hands before attending births. When this test was actually performed in the 1800s, the results matched the expectations, forming a strong scientific argument in support of the idea—and hand-washing!

Scientific idea + Expectations + Observations = **Scientific argument**

Though the elements of a scientific argument (scientific idea, expectations generated by the idea, and relevant observations) are always related in the same logical way, in terms of the process of science, those elements may be assembled in different orders. Sometimes the idea comes first and then scientists go looking for the observations that bear on it. Sometimes the observations are made first, and they suggest a particular idea. Sometimes the idea and the observations are already out there, and someone comes along later and figures out that the two might be related to one another.

Assembling a scientific argument

Testing ideas with evidence may seem like plain old common sense—and at its core, it is!—but there are some subtleties to the process:

- **Ideas can be tested in many ways.** Some tests are relatively straightforward (e.g., raising 1000 fruit flies and counting how many have red eyes), but some require a lot of time (e.g., waiting for the next appearance of Halley's Comet), effort (e.g., painstakingly sorting through thousands of microfossils), and/or the development of specialized tools (like a particle accelerator).
- **Evidence can reflect on ideas in many different ways.**
- **There are multiple lines of evidence and many criteria to consider in evaluating an idea.**
- **All testing involves making some assumptions.**

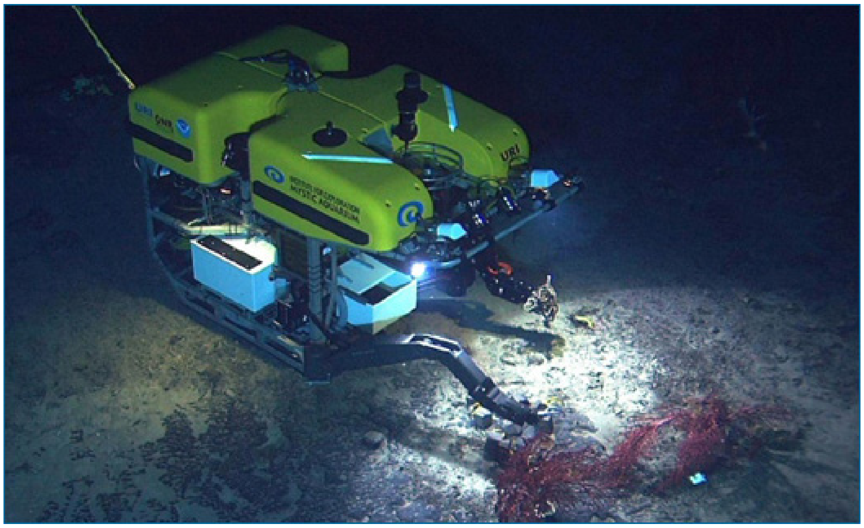
Despite these details, it's important to remember that, in the end, hypotheses and theories live and die by whether or not they work—in other words, whether they are useful in explaining data, generating expectations, providing satisfying explanations, inspiring research questions, answering questions, and solving problems. Science filters through many ideas and builds on those that *work*!

Tactics for testing ideas

Experiments are one way to test some sorts of ideas, but science doesn't live on experiment alone. There are many other ways to scientifically test ideas too …

What are experiments?

An experiment is a test that involves manipulating some factor in a system in order to see how that affects the outcome. Ideally, experiments also involve controlling as many other factors as possible in order to isolate the cause of the experimental results. Experiments can be quite simple tests set up in a lab—like rolling a ball down different inclines to see how the angle affects the rolling time. But large-scale experiments can also be performed out in the real world—for example, classic experiments in ecology involved removing a species of barnacles from intertidal rocks on the Scottish coast to see how that would affect other barnacle species over time. But whether they are large- or small-scale, performed in the lab or in the field, and require years or mere milliseconds to complete, experiments are distinguished from other sorts of tests by their reliance on the intentional manipulation of some factors and, ideally, the control of others.



Experiments can even take place on the ocean floor. In this case, a remotely-operated vehicle retrieves basalt cubes that were placed almost a year earlier as potential sites for new coral attachment. The experiment is examining how coral reproduce and disperse.

Natural experiments

Some aspects of the natural world aren't manipulable, and hence can't be studied with direct experiments. We simply can't go back in time and introduce finches to three separate island groups to see how they evolve. We can't move the planets around to see how their orbits would be altered by a new configuration. And we can't cause volcanoes to erupt in order to investigate how they affect the ecosystems that surround them. However, such ancient, distant, and large-scale phenomena *can* be studied with the methods described below, and in many cases, we can observe the results of natural experiments on these systems. Natural experiments occur when the universe, in

Though we can't experimentally manipulate phenomena like volcanoes, we can carefully observe the outcomes of these natural experiments. In this photo, a geologist takes a lava sample from the Kilauea volcano in Hawaii.

Remotely-operated vehicle photo provided by NOAA; Kilauea photo provided by U.S. Department of Interior, U.S. Geological Survey

a sense, performs an experiment for us—that is, the relevant experimental set-up already exists, and all we have to do is observe the results.

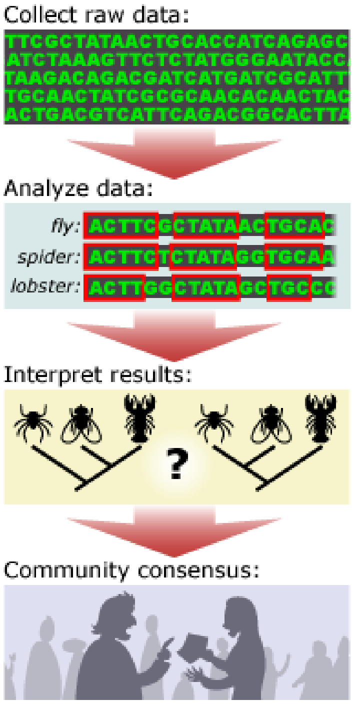
A *T. rex* tooth can tell us a lot about what this animal ate.

More than just experiments

For many ideas in science, testing via experiment is impossible, inappropriate, or only part of the picture. In those cases, testing is often a matter of making the right observations. For example, we can't actually experiment on distant stars in order to test ideas about which nuclear reactions occur within them, but we *can* test those ideas by building sensors that allow us to observe what forms of radiation the stars emit. Similarly, we can't perform experiments to test ideas about what *T. rex* ate, but we *can* test those ideas by making detailed observations of their fossilized teeth and comparing those to the teeth of modern organisms that eat different foods. And of course, many ideas can be tested by both experiment and through straightforward observation. For example, we can test ideas about how chlorofluorocarbons interact with the ozone layer by performing chemical experiments in a lab and through observational studies of the atmosphere.

Digging into data

Evaluating an idea in light of the evidence should be simple, right? Either the results match the expectations generated by the idea (thus, supporting it) or they don't (thus, refuting it). Sometimes the process is relatively simple (e.g., drilling into a coral atoll either reveals a thick layer of coral or a thin veneer), but often it is not. The real world is messy and complex, and often, interpreting the evidence relating to an idea is not so clear-cut. To complicate things further, we often have to weigh multiple lines of evidence that are all relevant to the validity of a particular idea.



Tests typically generate what scientists think of as raw data—unaltered observations, descriptions, or measurements—but those must be analyzed and interpreted. Data become evidence only when they have been interpreted in a way that reflects on the accuracy or inaccuracy of a scientific idea. For example, an investigation of the evolutionary relationships among crustaceans, insects, millipedes, spiders, and their relatives might tell us the genetic sequence of a particular gene for each organism. This is raw data, but what does it mean? A long series of the As, Ts, Gs, and Cs that make up genetic sequences don't, by themselves, tell us whether insects are more closely related to crustaceans or to spiders. Instead, those data must be analyzed through statistical calculations, tabulations, and/or visual representations. In this case, a biologist might begin to analyze the genetic data by aligning the different sequences, highlighting similarities and differences, and performing calculations to compare the different sequences. Only then can she interpret the results and figure out whether or not they support the hypothesis that insects are more closely related to crustaceans than to spiders.

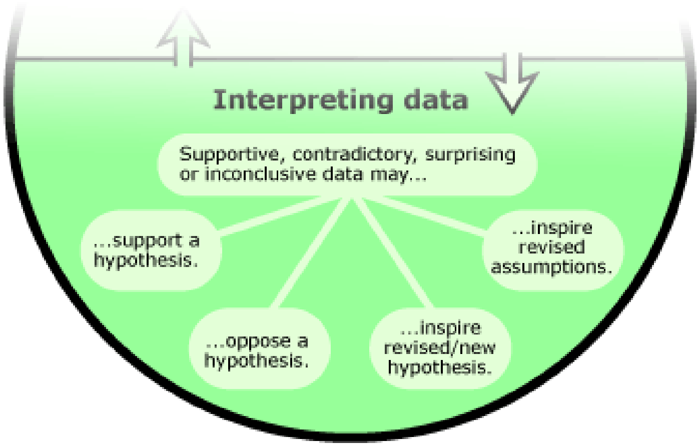
Furthermore, the same data may be interpreted in different ways. So another scientist could analyze the same genetic data in a new way and come to a different conclusion about the relationships between insects, crustaceans, and spiders. Ultimately, the scientific community will come to a consensus about how a set of data should be interpreted, but this process may take some time and usually involves additional lines of evidence.

CALCULATING CONFIDENCE

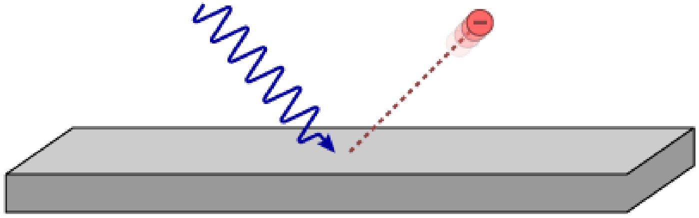
Interpreting test results often means dealing with uncertainty and error. "Now, hold on," you might be thinking, "I thought that science was supposed to build knowledge and *decrease* uncertainty and error." And that's true; however, when scientists draw a conclusion or make a calculation, they frequently try to give a statistical indication of how confident they are in the result. In everyday language, uncertainty and error mean that the answer is unclear or that a mistake has been made. However, when scientists talk about uncertainty and error, they are usually indicating their level of *confidence* in a number. So reporting a temperature to be 98.6° F (37° C) with an uncertainty of plus or minus 0.4° F actually means that we are highly confident that the true temperature falls between 98.2 and 99.0° F.

Reviewing test results

Scientists typically weigh *multiple* competing ideas about how something works and try to figure out which of those is most accurate based on the evidence. However, looking at the results of a test (whether the test is an experiment or another sort of study) often leads to surprises.



- **Evidence may lend support to one hypothesis over others.** For example, drilling into coral atolls and discovering a layer of coral thousands of feet thick clearly lent support to the idea that coral atolls form around subsiding volcanic islands, although, of course, many other lines of evidence also helped support that idea over competing explanations.
- **Evidence may help rule out some hypotheses.** Similarly, the results of the atoll drilling project helped refute a different idea—that atolls grow atop underwater mountains built up by oceanic debris, which would have fit with the observation of a thin layer of coral.
- **Evidence may lead to the revision of a hypothesis.** For example, experiments and observations had long supported the idea that light consists of waves, but in 1905, Einstein showed that a well known (and previously unexplained) phenomenon—the photoelectric effect—made perfect sense if light consisted of discrete particles. This led physicists to modify their ideas about the nature of light: light was *both* wave-like *and* particle-like.

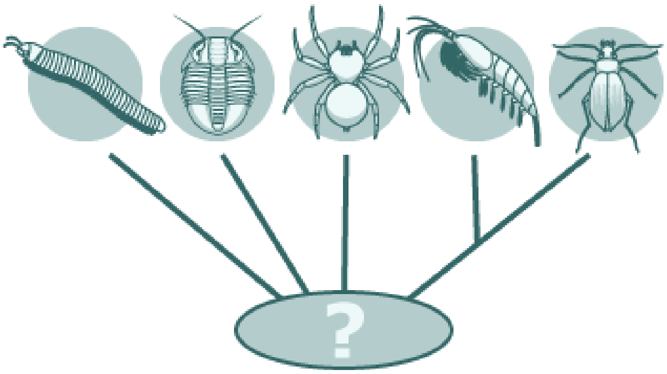


The photoelectric effect is a phenomenon in which electrons are emitted by a metal surface when certain frequencies of light strike it. This effect didn't make sense until Einstein suggested that light consisted of particles with discrete amounts of energy.

- **Evidence may reveal a faulty assumption, causing the scientist to revise his or her assumptions and possibly redesign the test.** For example, in the 1970s, geologists tried to test ideas about the timing of the transition between the Cretaceous and Tertiary periods by measuring the amount of iridium in the transitional rock layer. The test relied on the assumption that iridium was deposited at a low but constant, normal rate. However, to their surprise, the rock layer contained unusually large amounts of iridium, indicating that their original test design had been based on the false assumption of a low and constant deposition rate.

- **Evidence may be so surprising that a wholly new hypothesis or new research question is inspired.** Along similar lines, the unexpected discovery of large amounts of iridium at the Cretaceous-Tertiary boundary eventually inspired a new hypothesis about a different topic—that the end-Cretaceous mass extinction was triggered by a catastrophic asteroid impact.

- **Evidence may be inconclusive, failing to support any particular explanation over another.** For example, many biologists have investigated the anatomy and genetic sequences of the arthropods (crustaceans, insects, millipedes, spiders, and their relatives) in order to figure out how these groups are related. So far, the results have been inconclusive, not consistently supporting a single view of their interrelationships. Biologists continue to collect more evidence in order to resolve the question.

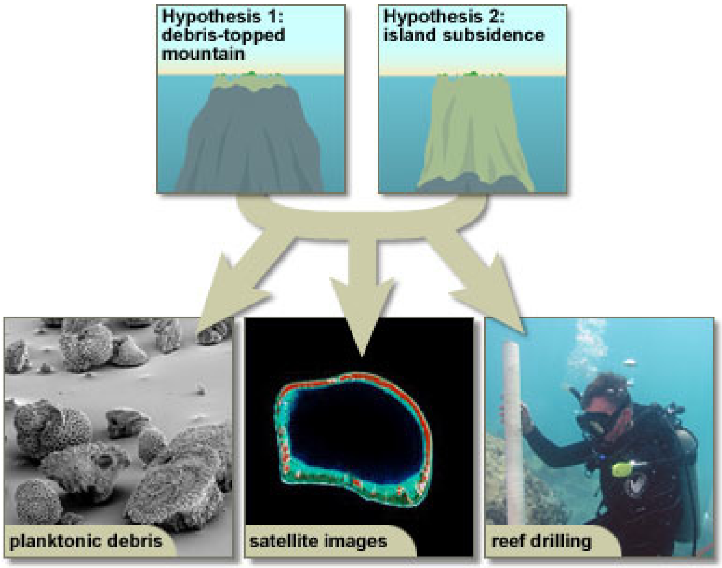


New evidence can feed back into the process of science in many ways. Most importantly, new evidence helps us evaluate ideas. To learn more about how science evaluates ideas, read on …

Asteroid image provided by Don Davis and NASA

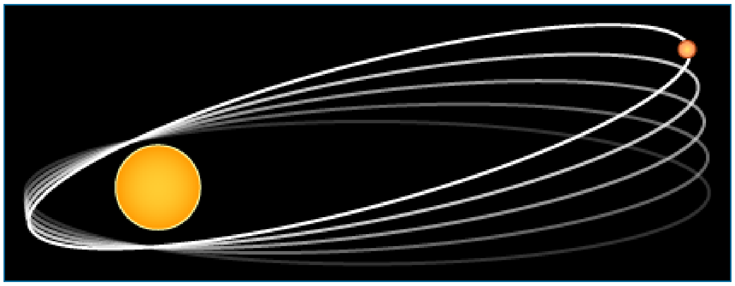
Competing ideas: A perfect fit for the evidence

We've seen that evaluating an idea in science is not always a matter of one key experiment and a definitive result. Scientists often consider multiple ideas at once and test those ideas in many different ways. This process generates multiple lines of evidence relevant to each idea. For example, two competing ideas about coral atoll formation (island subsidence vs. formation on debris-topped underwater mountains) were evaluated based on multiple lines of evidence, including observations of reef and atoll shapes, island geology, studies of the distribution of planktonic debris, and reef drilling. Furthermore, different lines of evidence are assembled cumulatively over time as different scientists work on the problem and as new technologies are developed. Because of this, the evaluation of scientific ideas is provisional. Science is always willing to resurrect or reconsider an idea if warranted by new evidence.



It's no wonder then that the evaluation of scientific ideas is iterative and depends upon interactions within the scientific community. Ideas that are accepted by that community are the best explanations we have so far for how the natural world works. But what makes one idea better than another? How do we judge the accuracy of an explanation? The most important factors have to do with evidence—how well our actual observations fit the expectations generated by the hypothesis or theory. The better the match, the more likely the hypothesis or theory is accurate.

- **Scientists are more likely to trust ideas that more closely explain the actual observations.** For example, the theory of general relativity explains why Mercury's orbit around the Sun shifts as much as it does with each lap (Mercury is close enough to the Sun that it passes through the area where space-time is dimpled by the Sun's mass). Newtonian mechanics, on the other hand, suggests that this aberration in Mercury's orbit should be much smaller than what we actually observe. So general relativity more closely explains our observations of Mercury's orbit than does Newtonian mechanics.



Mercury's orbit around the sun shifts a bit with each lap, which can be explained by the theory of general relativity.

- **Scientists are more likely to trust ideas that explain more disparate observations.** For example, many scientists in the 17th and 18th centuries were

Atoll satellite image by NASA/Goddard Space Flight Center; coral core sample photo by Jeff Anderson, Florida Keys National Marine Sanctuary

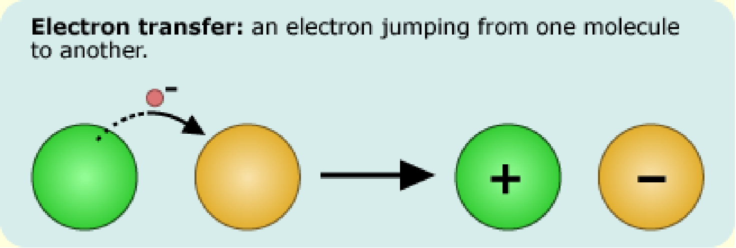
puzzled by the presence of marine fossils high in the Alps of Europe. Some tried to explain their presence with a massive flood, but this didn't address why these fossils were of animals that had gone extinct. Other scientists suggested that sea level had risen and dropped several times in the past, but had no explanation for the height of the mountains. However, the theory of plate tectonics helped explain all these disparate observations (high mountains, uplifted chunks of the seafloor, and rocks so ancient that they contained the fossils of long extinct organisms) and many more, including the locations of volcanoes and earthquakes, the shapes of the continents, and huge rifts in the ocean's floor.

- **Scientists are more likely to trust ideas that explain observations that were previously inexplicable, unknown, or unexpected.** For an example, see Rudolph Marcus's story below …

JUMPING ELECTRONS!

As chemical reactions go, electron transfers might seem to be minor players: an electron jumps between molecules without even breaking a chemical bond. Nevertheless, such reactions are essential to life. Photosynthesis, for example, depends on passing electrons from one molecule to another to transfer energy from light to molecules that can be used by a cell. Some of these reactions proceed at breakneck speeds, and others are incredibly slow—but why should two reactions, both involving a single electron transfer, vary in speed?

Rudolph Marcus



In the 1950s, Rudolph Marcus and his colleagues developed a simple mathematical explanation for how the rate of the reaction changes based on the amount of free energy absorbed or released by the system. The explanation fit well with actual observations that had been made at the time, but it also generated an unintuitive expectation—that some reactions, which release a lot of energy, should proceed surprisingly slowly, and should slow down as the energy released increases. It was a bit like suggesting that for most ski slopes, a steeper incline means faster speeds, but that on the very steepest slopes, skiers will slide down slowly! The expectation generated by Marcus's idea was entirely unanticipated, but nevertheless, almost 25 years later, experiments confirmed the surprising expectation, supporting the idea and winning Marcus the Nobel Prize.

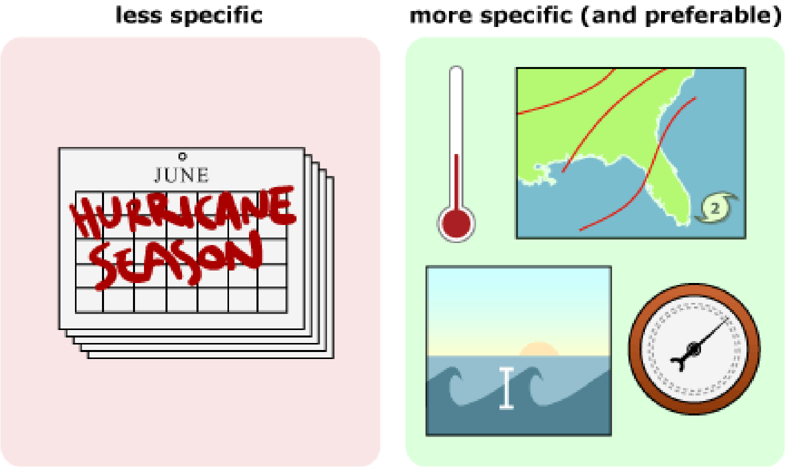
What happens when science can't immediately produce the evidence relevant to an idea? Absence of evidence isn't evidence of absence. Science doesn't reject an idea just because the relevant evidence isn't readily available. Sometimes, we have to wait for an event (e.g., the next solar eclipse), hope for a key discovery (e.g., transitional whale fossils in the deserts of Pakistan), or try to develop a new technology (e.g., a more powerful telescope), and until then, must suspend our judgment of an idea.

Rudolph Marcus image provided by the California Institute of Technology

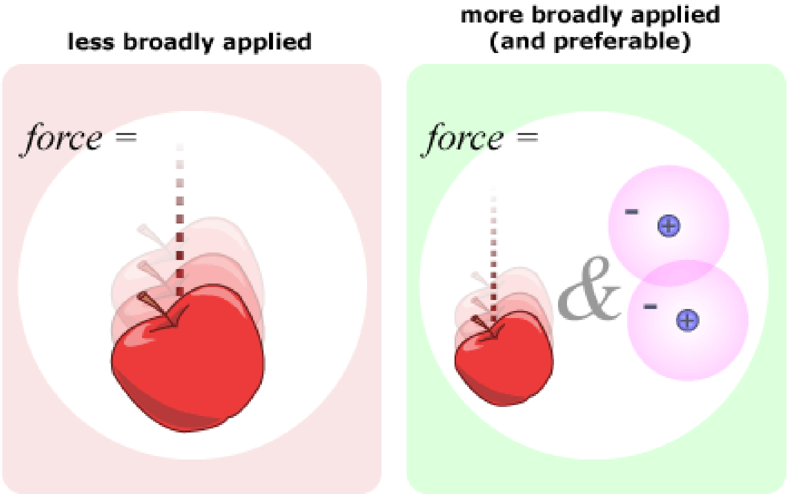
Competing ideas: Other considerations

In evaluating scientific ideas, evidence is the main arbiter; however, sometimes the available evidence supports several different hypotheses or theories equally well. In those cases, science often applies other criteria to evaluate the explanations. Though these are more like rules of thumb than firm standards, scientists are more likely to put their trust in ideas that:

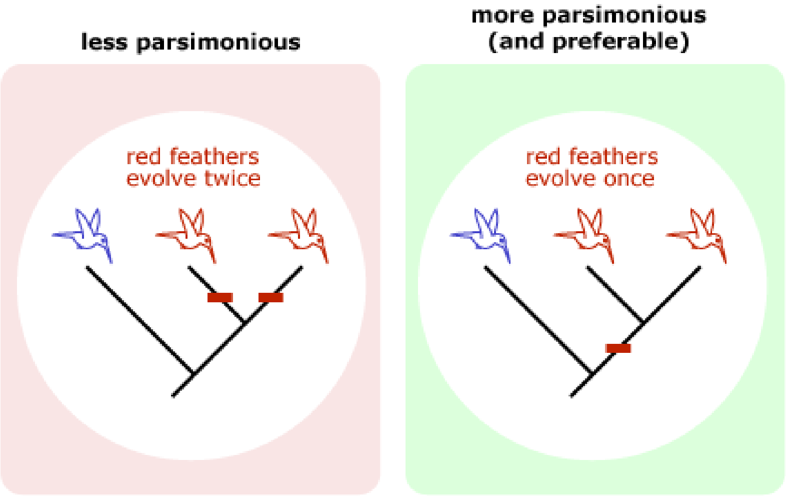
- **generate more specific expectations (i.e., are more testable).** For example, a hypothesis about hurricane formation that generates more specific expectations about the conditions under which they are likely to form might be preferred over one that just suggests what time of year they should be common.


less specific **more specific (and preferable)**

- **can be more broadly applied.** For example, a theory about the nature of force that applies to both macroscopic interactions (e.g., the pull of Earth's gravity on an apple) and subatomic interactions (e.g., between protons and electrons) might be preferred over one that only applies to interactions between large objects.


less broadly applied **more broadly applied (and preferable)**

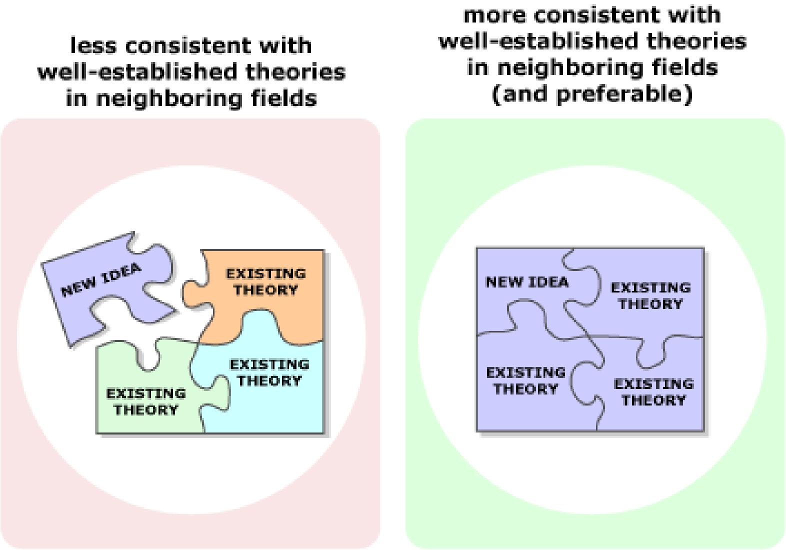
- **are more parsimonious.** For example, a hypothesis about the evolutionary relationships among hummingbird species that involves only 70 evolutionary changes might be preferred over one that postulates 200 changes.



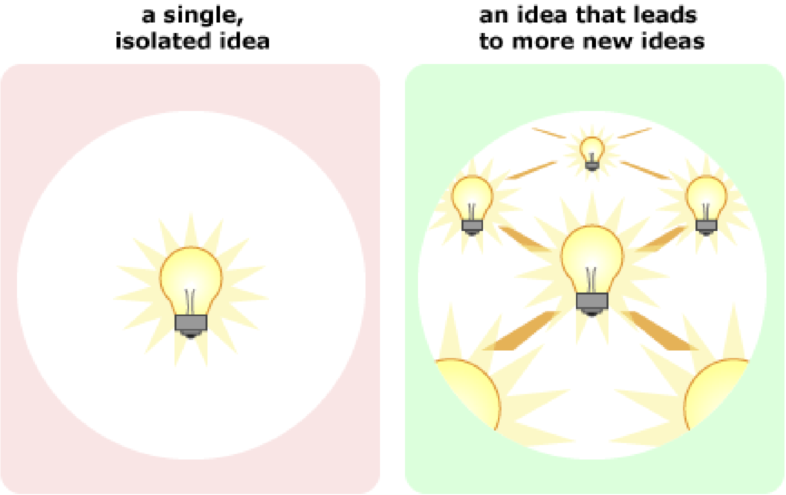
THE PRINCIPLE OF PARSIMONY

The principle of parsimony suggests that when two explanations fit the observations equally well, a simpler explanation should be preferred over a more convoluted and complex explanation. For a hypothetical illustration, imagine that we have only a few lines of evidence in a case of cookie jar pilfering: a broken and empty cookie jar, a crumb trail leading to the doggie door, and Fido's bellyache. Perhaps Fido stole the cookies, or perhaps it was all a set-up: the parrot knocked the jar off the table and ate the cookies, the cat tracked the crumbs to the door, and Fido has a bellyache because he got into the neighbor's garbage can. Both explanations fit all the available evidence—but which is more parsimonious?

- **are more consistent with well-established theories in neighboring fields.** For example, a major argument against the theory of evolution when Darwin first proposed it was that the theory didn't mesh with what was known about the age of the Earth at the time. Physicists had estimated the Earth to be just 100 million years old, a length of time that was deemed insufficient for evolution to account for the diversity of life on Earth today. However, as our understanding of geology and physics have improved, the age of the Earth has been more accurately pegged at several billion years old—a view that squares well with the idea that all life on Earth evolved from a common ancestor.



- **generate more new ideas.** For example, evolutionary biology not only helps us understand the history of life on Earth, but also generates useful ideas that can be applied to many fields—most notably in medicine, agriculture, and conservation. The power of evolution to generate fruitful ideas in many other fields reinforces its value as a theory.

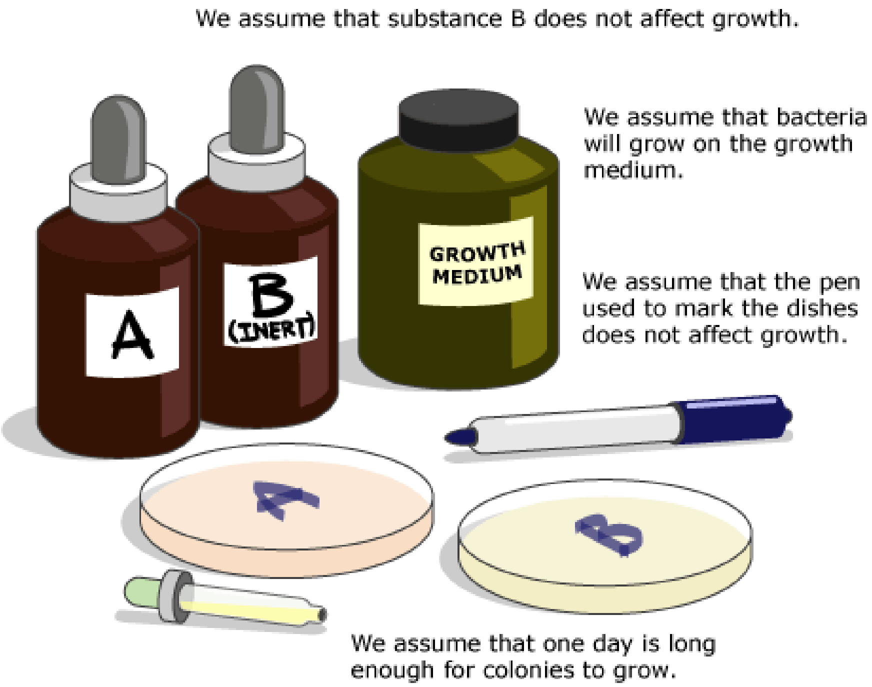


All this might seem complex, but it's important to keep the main point in mind. These criteria are just guidelines for identifying ideas that work—ideas that fit the evidence, generate new expectations, inspire further research, and seem to be accurate explanations for how the world works!

Making assumptions

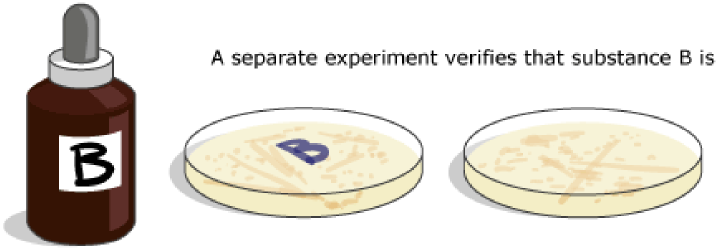
Much as we might like to avoid it, *all* scientific tests involve making assumptions—many of them justified. For example, imagine a very simple test of the hypothesis that substance A stops bacterial growth. Some Petri dishes are spread with a mixture of substance A and bacterial growth medium, and others are spread with a mixture of inert substance B and bacterial growth medium. Bacteria are spread on all the Petri dishes, and one day later, the plates are examined to see which fostered the growth of bacterial colonies and which did not. This test is straightforward, but still relies on many assumptions: we assume that the bacteria can grow on the growth medium, we assume that substance B does not affect bacterial growth, we assume that one day is long enough for colonies to grow, and we assume that the color pen we use to mark the outside of the dishes is not influencing bacterial growth.

Even a fairly straightforward experiment will rely on some assumptions:

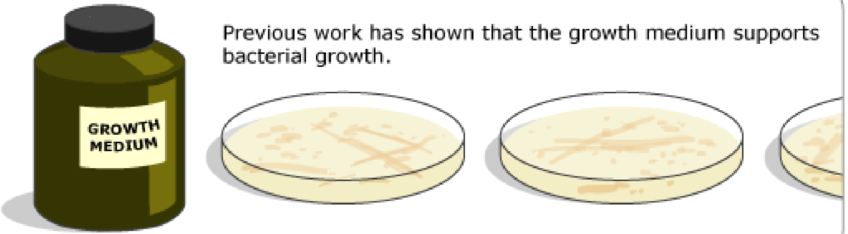


Technically, these are all assumptions, but they are perfectly reasonable ones that can be tested. The scientist performing the experiment described above would justify many of her assumptions by performing additional tests in parallel with the experimental ones. For example, she would separately test whether substance B affects bacterial growth to check that it was indeed inert as she'd assumed. Other assumptions are justified by past tests performed by other scientists. For instance, the question of whether or not bacteria can grow on the growth medium would have been studied by many previous researchers. And some assumptions might remain untested simply because all of our knowledge about the field suggests that the assumption is a safe one (e.g., we know of no reason why bacteria should multiply faster when their dishes are marked with a red, rather than a green, pen). All tests involve assumptions, but most of these are assumptions that can and have been verified separately.

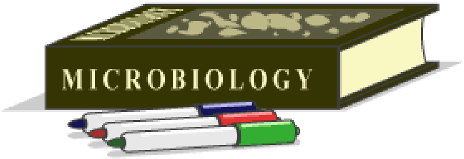
Check assumptions:



A separate experiment verifies that substance B is inert.



Previous work has shown that the growth medium supports bacterial growth.

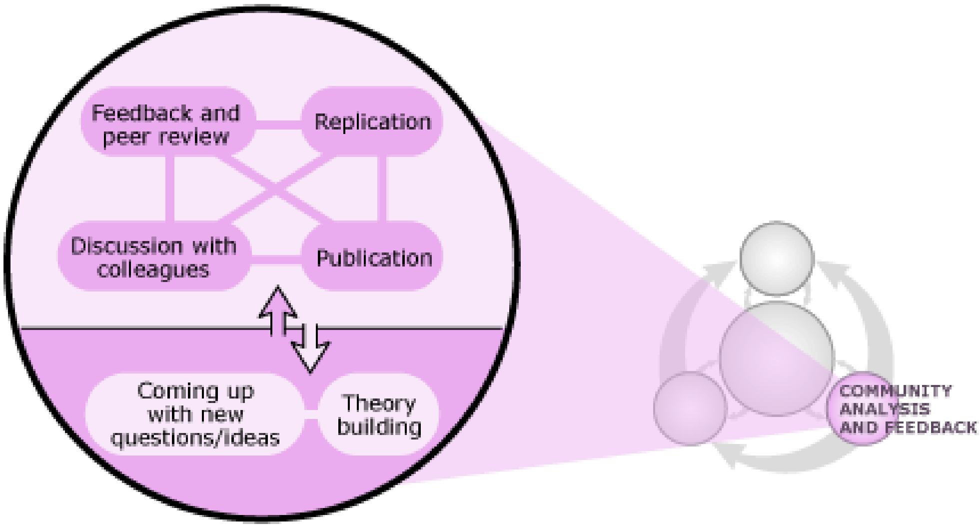


The sum of all knowledge about bacterial growth suggests no reason to think that the writing on the outside of the dish matters.

Nevertheless, when evaluating an idea in light of test results, it's important to keep in mind the test's assumptions and how well-supported they are. If an expectation generated by an idea is not borne out in a test, it might be because the idea is wrong and should be rejected, or it might be that the idea is right, but an assumption of the test has been violated. And if the test results end up lending support to the idea, it might be because the idea is correct and should be accepted, or it might be because a violated assumption has produced a false positive result.

Analysis within the scientific community

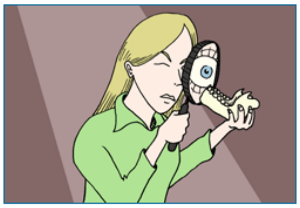
The stereotype of a scientist (a recluse who speaks in a jumble of technical jargon) doesn't exactly paint a picture of someone whose work depends on communication and community, but in fact, interactions within the scientific community are essential components of the process of science. Scientists don't work in isolation. Though they sometimes work alone (fussing over an experiment in the lab, trekking through the Amazon, scribbling on a notepad at a desk), scientists are just as likely to be found emailing colleagues, arguing with other scientists over coffee, sitting in on a lab meeting, or preparing conference presentations and journal articles. In science, even those few working entirely on their own must ultimately share their work for it to become part of the lasting body of scientific knowledge.



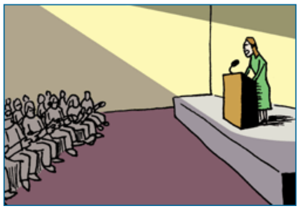
In terms of the process of science, members of the community play several essential and direct roles:

Fact checker/critic: the community evaluates evidence and ideas. The scrutiny of the scientific community helps ensure that evidence meets high standards of quality, that all relevant lines of evidence are explored, and that judgments are not based on flawed reasoning.

Innovator/visionary: the community generates new ideas. Interactions within a diverse and creative community spark ideas about new lines of evidence, new interpretations of existing data, new applications, new questions, and alternate explanations—all of which help science move forward.



Watchdog/whistleblower: the community helps eliminate bias and fraud by keeping watchful eye. Though fraud is rare and bias often unintentional, the occasional cases of such offenses are detected through the scrutiny and ongoing work of the scientific community.



Cheerleader/taskmaster: the community motivates scientists. The community offers the prospects of recognition, esteem, and a scientific legacy—payoffs which help motivate many scientists in their investigations.

Interactions within the scientific community and the scrutiny they entail take time and can slow the process of science. However, these interactions are crucial because they help ensure that science provides us with more and more accurate and useful descriptions of how the world works.

So how, exactly, does the scientific community manage to play all these challenging roles? To learn more about key features of community analysis—publication, peer review, and replication—read on …

Publish or perish?

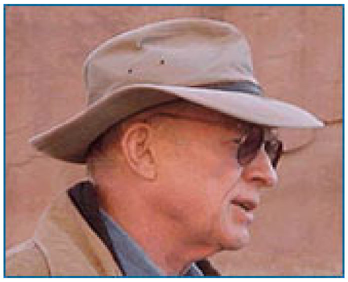
Among academics, the maxim "publish or perish" (i.e., publish your research or risk losing your job) is a threatening reminder of the importance of publication. Despite its cynicism, the phrase makes an important point: publishing findings, hypotheses, theories, and the lines of reasoning and evidence relevant to them is critical to the progress of science. The scientific community can only fulfill its roles as fact checker, visionary, whistleblower, and cheerleader if it has trusted information about the work of community members. Scientists distribute information about their ideas in many ways—informally communicating with colleagues, making presentations at conferences, writing books, etc.—but among these different modes of communication, peer-reviewed journal articles are especially important.

What's in a scientific journal article?

A journal article is a formal, souped-up version of the standard high school lab report. In journal articles, scientists (usually a group of collaborators) describe a study and report any details one might need to evaluate that study—background information, data, statistical results, graphs, maps, explanations of how the study was performed and how the researchers drew their conclusions, etc. These articles are published in scientific journals either in print or on the internet. Print journals look much like any magazine, except that they are chock full of firsthand reports of scientific research. Journals distribute scientific information to researchers all around the world so that they can keep current in their fields and evaluate the work of their peers.

Journal articles neaten up the messy process of science, presenting ideas, evidence, and reasoning in a way that's easy to understand—in contrast to the often circuitous (and sometimes tedious) process of science. For an example, check out Walter Alvarez's story below …

UNTANGLING A TWISTED PATH

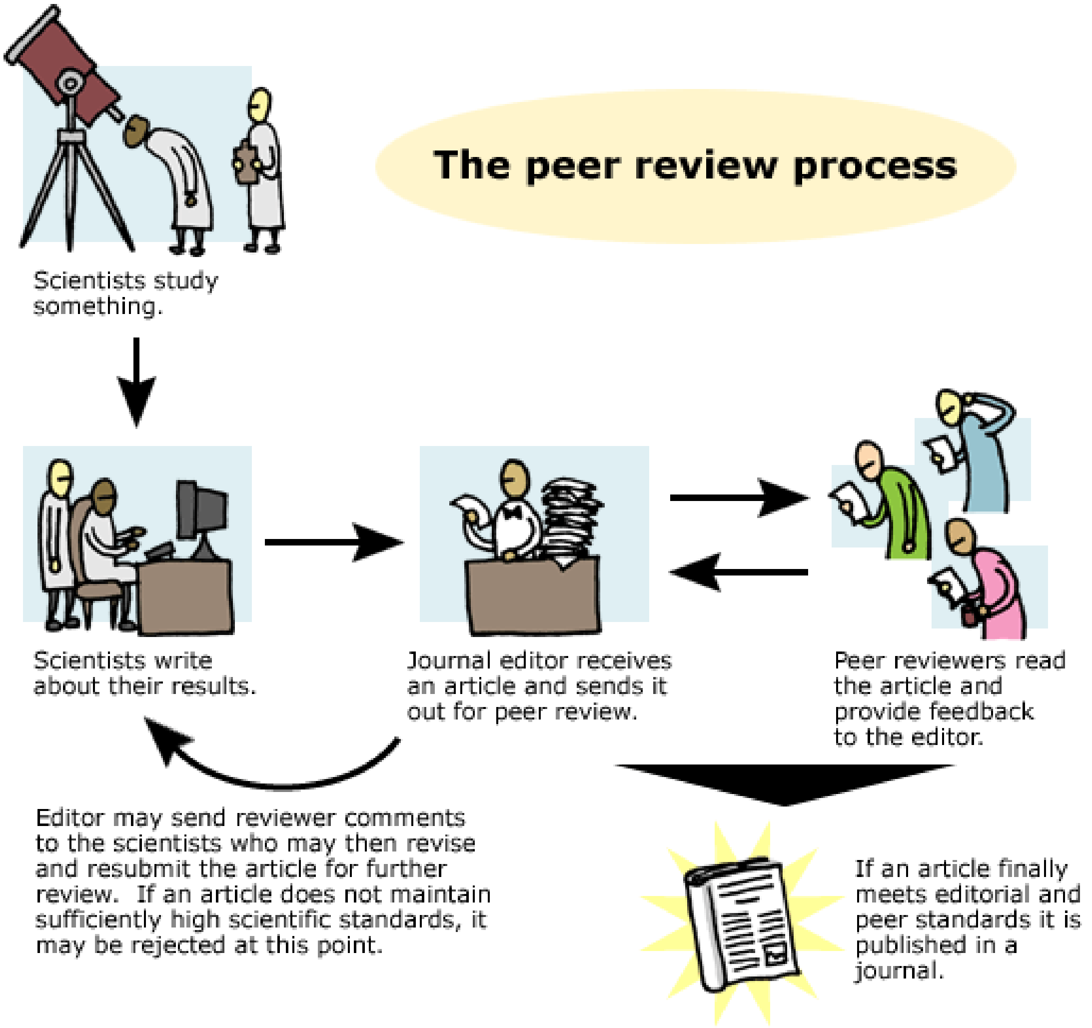

Walter Alvarez

In 1980, in the journal *Science*, Walter Alvarez and his colleagues published a scientific article describing their controversial new hypothesis that the dinosaur extinction was triggered by a massive asteroid impact. Despite its splashy and novel topic, the article laid out its hypothesis and evidence in the conventional way—linearly—which allowed colleagues in geology and paleontology to quickly understand and evaluate the research. Though helpful for scientific communication, this linear presentation can give the impression that an investigation has been plotted out from the beginning—but in fact, Alvarez's study was far from linear. He stumbled onto his hypothesis unexpectedly, originally setting out to study the tectonic movements of the Italian peninsula. After an intriguing series of twists, turns, false starts, inspirations, and rejected hypotheses, he and his colleagues found that they had completed a rather different, but compelling, investigation.

Scrutinizing science: Peer review

Peer review does the same thing for science that the “inspected by #7” sticker does for your t-shirt: provides assurance that someone who knows what they’re doing has double-checked it. In science, peer review typically works something like this:

1) A group of scientists completes a study and writes it up in the form of an article. They submit it to a journal for publication.
2) The journal’s editors send the article to several other scientists who work in the same field (i.e., the “peers” of peer review).
3) Those reviewers provide feedback on the article and tell the editor whether or not they think the study is of high enough quality to be published.
4) The authors may then revise their article and resubmit it for consideration.
5) Only articles that meet good scientific standards (e.g., acknowledge and build upon other work in the field, rely on logical reasoning and well-designed studies, back up claims with evidence, etc.) are accepted for publication.



The peer review process

Scientists study something.

Scientists write about their results.

Journal editor receives an article and sends it out for peer review.

Peer reviewers read the article and provide feedback to the editor.

Editor may send reviewer comments to the scientists who may then revise and resubmit the article for further review. If an article does not maintain sufficiently high scientific standards, it may be rejected at this point.

If an article finally meets editorial and peer standards it is published in a journal.

Peer review and publication are time-consuming, frequently involving more than a year between submission and publication. The process is also highly competitive. For example, the highly-regarded journal *Science* accepts less than 8% of the articles it receives, and *The New England Journal of Medicine* publishes just 6% of its submissions.

Peer-reviewed articles provide a trusted form of scientific communication. Even if you are unfamiliar with the topic or the scientists who authored a particular study, you can trust peer-reviewed work to meet certain standards of scientific quality. Since scientific knowledge is cumulative and builds on itself, this trust is particularly important. No scientist would want to base their own work on someone else's unreliable study! Peer-reviewed work isn't necessarily correct or conclusive, but it does meet the standards of science. And that means that once a piece of scientific research passes through peer review and is published, science must deal with it somehow—perhaps by incorporating it into the established body of scientific knowledge, building on it further, figuring out why it is wrong, or trying to replicate its results.

PEER REVIEW: NOT JUST SCIENCE

Many fields outside of science use peer review to ensure quality. Philosophy journals, for example, make publication decisions based on the reviews of other philosophers, and the same is true of scholarly journals on topics as diverse as law, art, and ethics. Even those outside the research community often use some form of peer review. Figure-skating championships may be judged by former skaters and coaches. Wine-makers may help evaluate wine in competitions. Artists may help judge art contests. So while peer review is a hallmark of science, it is not unique to science.

Copycats in science: The role of replication

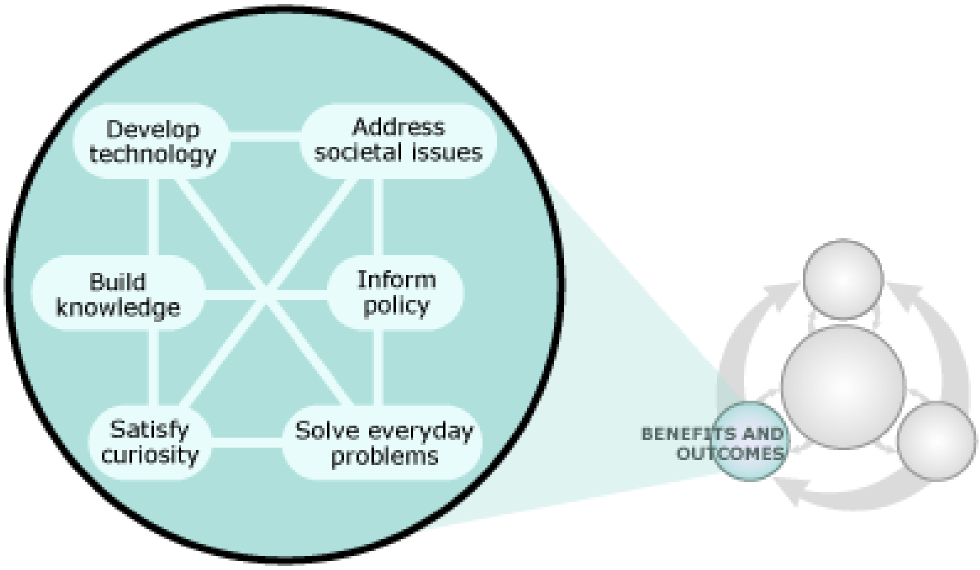
Scientists aim for their studies' findings to be replicable—so that, for example, an experiment testing ideas about the attraction between electrons and protons should yield the same results when repeated in different labs. Similarly, two different researchers studying the same dinosaur bone in the same way should come to the same conclusions regarding its measurements and composition. This goal of replicability makes sense. After all, science aims to reconstruct the unchanging rules by which the universe operates, and those same rules apply, 24 hours a day, seven days a week, from Sweden to Saturn, regardless of who is studying them. If a finding can't be replicated, it suggests that our current understanding of the study system or our methods of testing are insufficient.

Does this mean that scientists are constantly repeating what others before them have already done? No, of course not—or we would never get anywhere at all. The process of science doesn't require that every experiment and *every* study be repeated, but many are, especially those that produce surprising or particularly important results. In some fields, it is standard procedure for a scientist to replicate his or her own results before publication in order to ensure that the findings were not due to some fluke or factors outside the experimental design.

The desire for replicability is part of the reason that scientific papers almost always include a *methods* section, which describes exactly how the researchers performed the study. That information allows other scientists to replicate the study and to evaluate its quality, helping ensure that occasional cases of fraud or sloppy scientific work are weeded out and corrected.

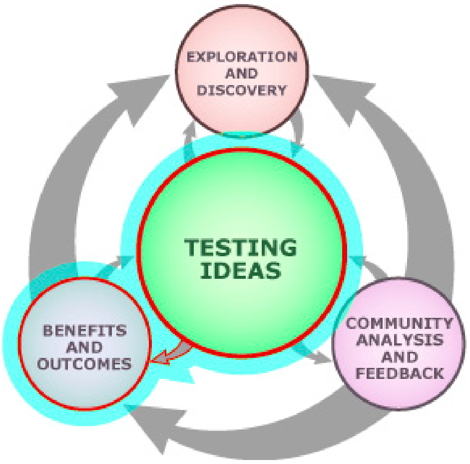
Benefits of science

The process of science is a way of building knowledge about the universe — constructing new ideas that illuminate the world around us. Those ideas are inherently tentative, but as they cycle through the process of science again and again and are tested and retested in different ways, we become increasingly confident in them. Furthermore, through this same iterative process, ideas are modified, expanded, and combined into more powerful explanations. For example, a few observations about inheritance patterns in garden peas can—over many years and through the work of many different scientists—be built into the broad understanding of genetics offered by science today. So although the process of science is iterative, ideas do not churn through it repetitively. Instead, the cycle actively serves to construct and integrate scientific knowledge.

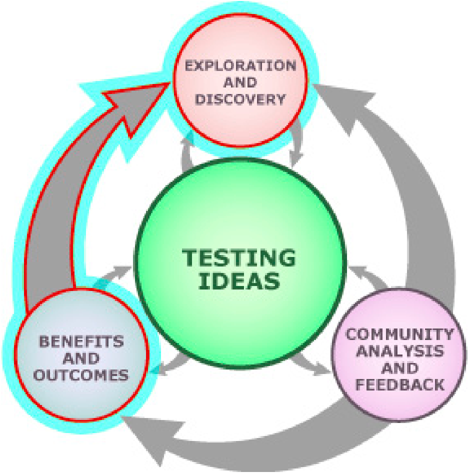


And that knowledge is useful for all sorts of things: from designing bridges, to slowing climate change, to prompting frequent hand washing during flu season. Scientific knowledge allows us to develop new technologies, solve practical problems, and make informed decisions—both individually and collectively. Because its products are so useful, the process of science is intertwined with those applications:

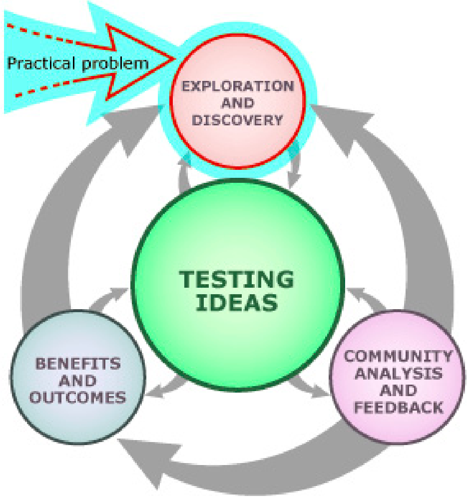
- **New scientific knowledge may lead to new applications.**
  For example, the discovery of the structure of DNA was a fundamental breakthrough in biology. It formed the underpinnings of research that would ultimately lead to a wide variety of practical applications, including DNA fingerprinting, genetically engineered crops, and tests for genetic diseases.



- **New technological advances may lead to new scientific discoveries.**
  For example, developing DNA copying and sequencing technologies has led to important breakthroughs in many areas of biology, especially in the reconstruction of the evolutionary relationships among organisms.



- **Potential applications may motivate scientific investigations.**
  For example, the possibility of genetically engineering bacteria to cheaply produce cutting-edge malaria drugs has motivated one researcher to continue his studies of synthetic biology.



The process of science and you

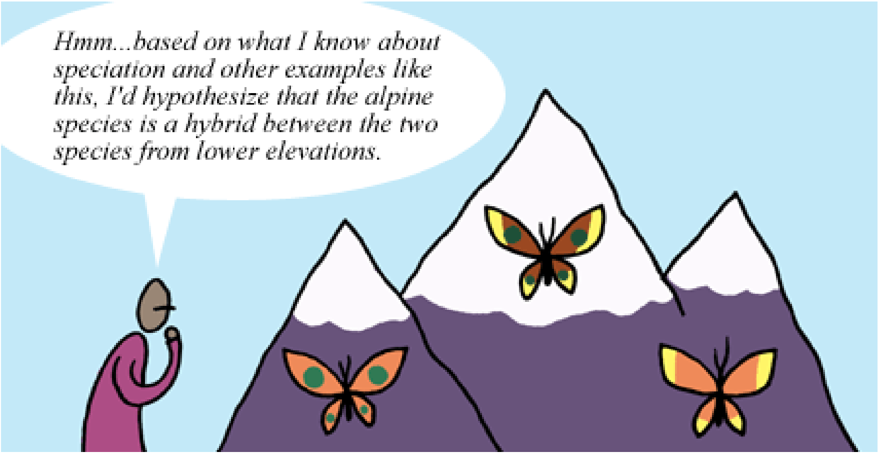
This flowchart represents the process of formal science, but in fact, many aspects of this process are relevant to everyone and can be used in your everyday life—even if you are not an amateur or professional scientist. Sure, some elements of the process really only apply to formal science (e.g., publication, feedback from the scientific community), but others are widely applicable to everyday situations (e.g., asking questions, gathering evidence, solving practical problems). Understanding the process of science can help anyone develop a scientific outlook on life.

Science at multiple levels

The process of science works at multiple levels—from the small scale (e.g., a comparison of the genes of three closely related North American butterfly species) to the large scale (e.g., a half-century-long series of investigations of the idea that geographic isolation of a population can trigger speciation). The process of science works in much the same way whether embodied by an individual scientist tackling a specific problem, question, or hypothesis over the course of a few months or years, or by a community of scientists coming to agree on broad ideas over the course of decades and hundreds of individual experiments and studies. Similarly, scientific explanations come at different levels:

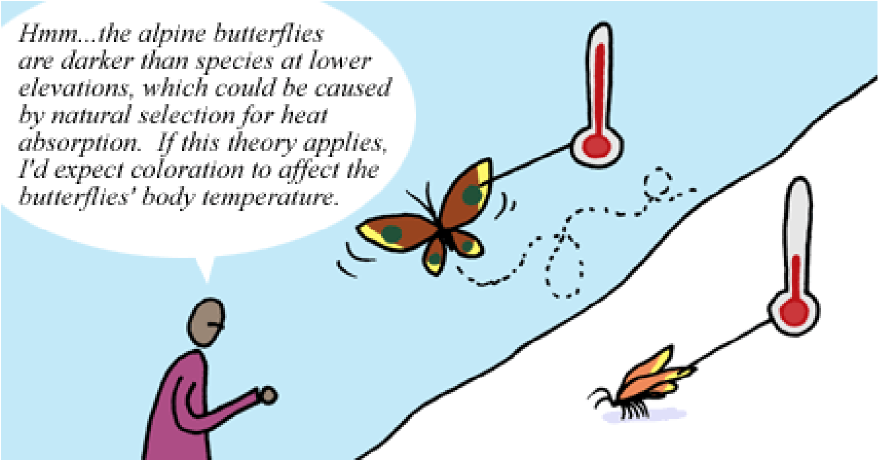
Hypotheses

Hypotheses are proposed explanations for a fairly narrow set of phenomena. These reasoned explanations are not guesses—of the wild or educated variety. When scientists formulate new hypotheses, they are usually based on prior experience, scientific background knowledge, preliminary observations, and logic. For example, scientists observed that alpine butterflies exhibit characteristics intermediate between two species that live at lower elevations. Based on these observations and their understanding of speciation, the scientists hypothesized that this species of alpine butterfly evolved as the result of hybridization between the two other species living at lower elevations.



Theories

Theories, on the other hand, are broad explanations for a wide range of phenomena. They are concise (i.e., generally don't have a long list of exceptions and special rules), coherent, systematic, predictive, and broadly applicable. In fact, theories often integrate and generalize many hypotheses. For example, the theory of natural selection broadly applies to all populations with some form of inheritance, variation, and differential reproductive success—whether that population is composed of alpine butterflies, fruit flies on a tropical island, a new form of life discovered on Mars, or even bits in a computer's memory. This theory helps us understand a wide range of observations (from the rise of antibiotic-resistant bacteria to the physical match between pollinators and their preferred flowers), makes predictions in new situations (e.g., that treating AIDS patients with a cocktail of medications should slow the evolution of the virus), and has proven itself time and time again in thousands of experiments and observational studies.



"JUST" A THEORY?

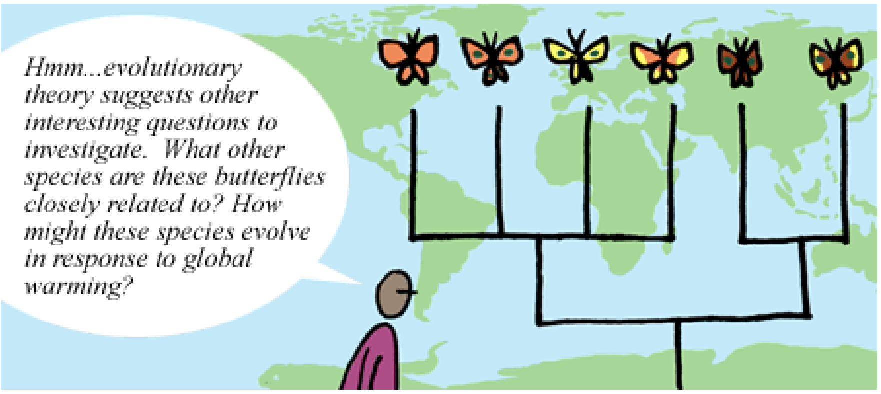
Occasionally, scientific ideas (such as biological evolution) are written off with the putdown "it's just a theory." This slur is misleading and conflates two separate meanings of the word *theory*: in common usage, the word theory means just a hunch, but in science, a theory is a powerful explanation for a broad set of observations. To be accepted by the scientific community, a theory (in the scientific sense of the word) must be strongly supported by many different lines of evidence. So biological evolution is a theory (it is a well-supported, widely accepted, and powerful explanation for the diversity of life on Earth), but it is not "just" a theory.

Words with both technical and everyday meanings often cause confusion. Even scientists sometimes use the word *theory* when they really mean hypothesis or even just a hunch. Many technical fields have similar vocabulary problems — for example, both the terms *work* in physics and *ego* in psychology have specific meanings in their technical fields that differ from their common uses. However, context and a little background knowledge are usually sufficient to figure out which meaning is intended.

Over-arching theories

Some theories, which we'll call over-arching theories, are particularly important and reflect broad understandings of a particular part of the natural world. Evolutionary theory, atomic theory, gravity, quantum theory, and plate tectonics are examples of this sort of over-arching theory. These theories have been broadly supported by multiple lines of evidence and help frame our understanding of the world around us.

Such over-arching theories encompass many subordinate theories and hypotheses, and consequently, changes to those smaller theories and hypotheses reflect a refinement (not an overthrow) of the over-arching theory. For example, when punctuated equilibrium was proposed as a mode of evolutionary change and evidence was found supporting the idea in some situations, it represented an elaborated reinforcement of evolutionary theory, not a refutation of it. Over-arching theories are so important because they help scientists choose their methods of study and mode of reasoning, connect important phenomena in new ways, and open new areas of study. For example, evolutionary theory highlighted an entirely new set of questions for exploration: How did this characteristic evolve? How are these species related to one another? How has life changed over time?



A MODEL EXPLANATION

Hypotheses and theories can be complex. For example, a particular hypothesis about meteorological interactions or nuclear reactions might be so complex that it is best described in the form of a computer program or a long mathematical equation. In such cases, the hypothesis or theory may be called a *model*.

Even theories change

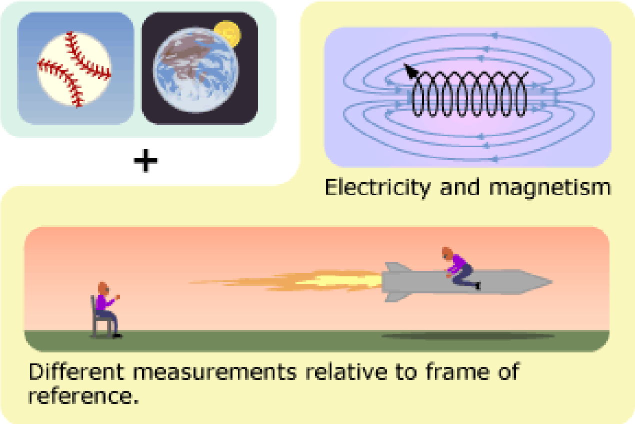
Accepted theories are the best explanations available so far for how the world works. They have been thoroughly tested, are supported by multiple lines of evidence, and have proved useful in generating explanations and opening up new areas for research. However, science is always a work in progress, and even theories change. How? We'll look at some over-arching theories in physics as examples:

- **Classical mechanics**
  In the 1600s, building on the ideas of others, Isaac Newton constructed a theory (sometimes called classical mechanics or Newtonian mechanics) that, with a simple set of mathematical equations, could explain the movement of objects both in space and on Earth. This single explanation helped us understand both how a thrown baseball travels and how the planets orbit the sun. The theory was powerful, useful, and has proven itself time and time again in studies; yet it wasn't perfect …

Classical mechanics explains:

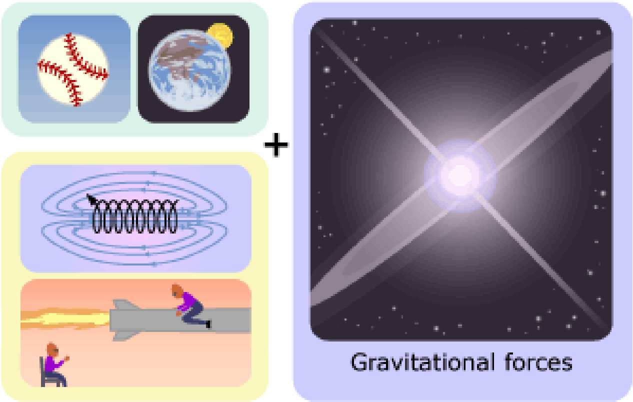
- **Special relativity**
  Classical mechanics was one-upped by Albert Einstein's theory of special relativity. In contrast to the assumptions of classical mechanics, special relativity postulated that as one's frame of reference (i.e., where you are and how you are moving) changes, so too do measurements of space and time—so that, for example, a person speeding away from Earth in a spacecraft will perceive the distance of the spacecraft's travel and the elapsed time of the trip to be different than would a person sitting at Cape Canaveral. Special relativity was preferred because it explained more phenomena: it accounted for what was known about the movement of large objects (from baseballs to planets) *and* helped explain new observations relating to electricity and magnetism.

Special relativity explains:



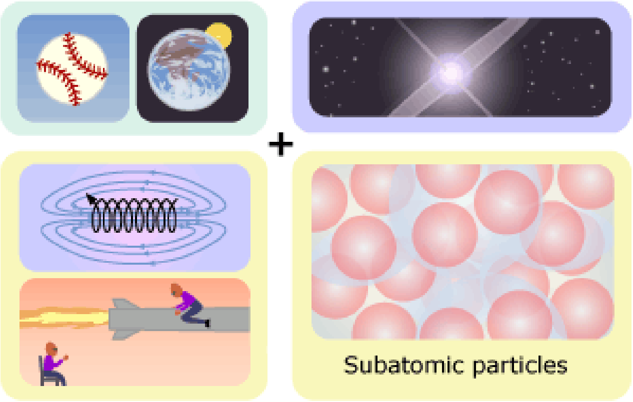
- **General relativity**
  Even special relativity was superseded by another theory. General relativity helped explain everything that special relativity did, as well as our observations of gravitational forces.

General relativity explains:



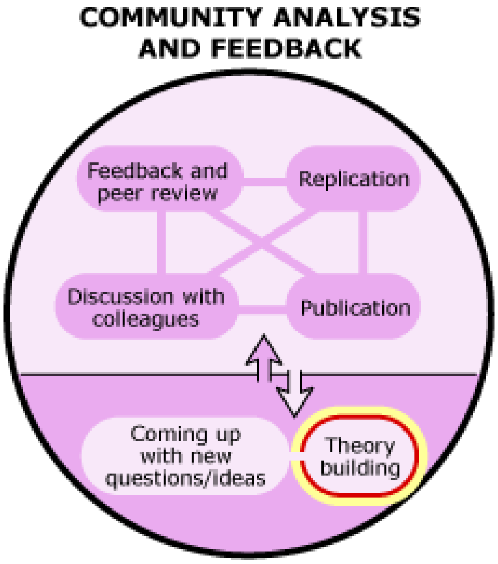
- **Our next theory …**
  General relativity has been enormously successful and has generated unique expectations that were later borne out in observations, but it too seems up for a change. For example, general relativity doesn't mesh with what we know about the interactions between extremely tiny particles (which the theory of quantum mechanics addresses). Will physicists develop a new theory that simultaneously helps us understand the interactions between the very large and the very small? Time will tell, but they are certainly working on it!

A new theory *might* explain:



All the theories described above worked—that is, they generated accurate expectations, were supported by evidence, opened up new avenues of research, and offered satisfying explanations. Classical mechanics, by the way, is still what engineers use to design airplanes and bridges, since it is so accurate in explaining how large (i.e., macroscopic) and slow (i.e., substantially slower than light) objects interact. Nevertheless, the theories described above did change. How? A well-supported theory may be accepted by scientists, even if the theory has some problems. In fact, few theories fit our observations of the world perfectly. There is usually some anomalous observation that doesn't seem to fit with our current understanding. Scientists assume that by working at such anomalies, they'll either disentangle them to see how they fit with the current theory or contribute to a new theory. And eventually that does happen: a new or modified theory is proposed that explains everything that the old theory explained plus other observations that didn't quite fit with the old theory. When that new or modified theory is proposed to the scientific community, over a period of time (it might take years), scientists come to understand the new theory, see why it is a superior explanation to the old theory, and eventually, accept the new theory.

Theory change is a community process of feedback, experiment, observation, and communication. It usually involves interpreting existing data in new ways and incorporating those views with new results. It may depend on a single definitive experiment or observation to change people's views, or it may involve many separate studies, eventually tipping the balance of evidence in favor of the new theory. The process may take some time since scientists don't always recognize good ideas right away, but eventually the scientific explanation that is more accurate will win out. This process of theory change often involves true scientific controversy, which is healthy, sparks additional research, and helps science move forward. True scientific controversy involves disagreements over how data should be interpreted, over which ideas are best supported by the available evidence, and over which ideas are worth investigating further.



SCIENTIFIC CONTROVERSY: TRUE OR FALSE?

Here, we've discussed true scientific controversy—a debate within the scientific community over which scientific idea is more accurate and should be used as the basis of future research. True scientific controversy involves competing scientific ideas that are evaluated according to the standards of science—i.e., fitting the evidence, generating accurate expectations, offering satisfying explanations, inspiring research, etc. However, occasionally, special interest groups try to misrepresent a non-scientific idea, which meets none of these standards, as inspiring scientific controversy.

Summing up the process

In this section, we've seen that the real process of science is not much like The Scientific Method often portrayed in textbooks. As opposed to the simple recipe of the linear scientific method, the *real* process of science is exciting, iterative, nonlinear, nuanced, depends upon the scientific community, and is intertwined with the society at large. The *real* process of science proceeds at multiple levels and sorts through many ideas, retaining and building upon those that work. However, despite all these complications, the core of that process, checking ideas against evidence from the natural world, is straightforward.