What is science?

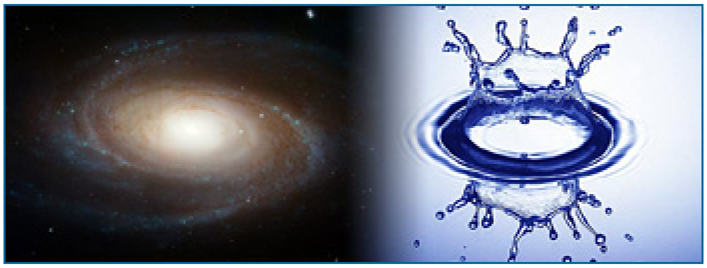
The word “science” probably brings to mind many different pictures: a fat textbook, white lab coats and microscopes, an astronomer peering through a telescope, a naturalist in the rainforest, Einstein’s equations scribbled on a chalkboard, the launch of the space shuttle, bubbling beakers …. All of those images reflect some aspect of science, but none of them provides a full picture because science has so many facets:

These images all show an aspect of science, but a complete view of science is more than any particular instance.

- **Science is both a body of knowledge and a process.** In school, science may sometimes seem like a collection of isolated and static facts listed in a textbook, but that’s only a small part of the story. Just as importantly, science is also a process of discovery that allows us to link isolated facts into coherent and comprehensive understandings of the natural world.
- **Science is exciting.** Science is a way of discovering what’s in the universe and how those things work today, how they worked in the past, and how they are likely to work in the future. Scientists are motivated by the thrill of seeing or figuring out something that no one has before.
- **Science is useful.** The knowledge generated by science is powerful and reliable. It can be used to develop new technologies, treat diseases, and deal with many other sorts of problems.
- **Science is ongoing.** Science is continually refining and expanding our knowledge of the universe, and as it does, it leads to new questions for future investigation. Science will never be “finished.”
- **Science is a global human endeavor.** People all over the world participate in the process of science. And you can too!

Diver photo provided by OAR/National Undersea Research Program (NURP); lab photo courtesy of Pacific Northwest National Laboratory; photo of geologists on volcano by J.D. Griggs; photo of scientist in corn field by Scott Bauer; image of Mars rover courtesy NASA/JPL-Caltech.

Discovery: The spark for science



"Eureka!" or "aha!" moments may not happen frequently, but they are often experiences that drive science and scientists. For a scientist, every day holds the possibility of discovery—of coming up with a brand new idea or of observing something that no one has ever seen before. Vast bodies of knowledge have yet to be built and many of the most basic questions about the universe have yet to be answered:

- What causes gravity?
- How do tectonic plates move around on Earth's surface?
- How do our brains store memories?
- How do water molecules interact with each other?

We don't know the complete answers to these and an overwhelming number of other questions, but the prospect of answering them beckons science forward.

EVERYDAY SCIENCE QUESTIONS

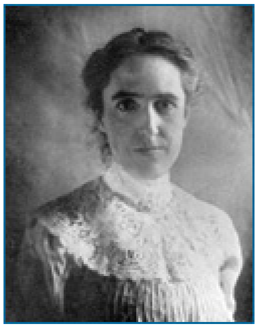
Scientific questions can seem complex (e.g., what chemical reactions allow cells to break the bonds in sugar molecules), but they don't have to be. You've probably posed many perfectly valid scientific questions yourself: how can airplanes fly, why do cakes rise in the oven, why do apples turn brown once they're cut? You can discover the answers to many of these "everyday" science questions in your local library, but for others, science may not have the answers yet, and answering such questions can lead to astonishing new discoveries. For example, we still don't know much about how your brain remembers to buy milk at the grocery store. Just as we're motivated to answer questions about our everyday experiences, scientists confront such questions at all scales, including questions about the very nature of the universe.

Discoveries, new questions, and new ideas are what keep scientists going and awake at night, but they are only one part of the picture; the rest involves a lot of hard (and sometimes tedious) work. In science, discoveries and ideas must be verified by multiple lines of evidence and then integrated into the rest of science, a process which can take many years. And often, discoveries are not bolts from the blue. A discovery may itself be the result of many years of work on a particular problem, as illustrated by Henrietta Leavitt's stellar discovery …

Photo of Spiral Galaxy M81 provided by NASA, ESA, and The Hubble Heritage Team (STScI/AURA); photo of water provided by Andrew Davidhazy.

Understanding Science

STELLAR SURPRISES



Henrietta Leavitt

Astronomers had long known about the existence of variable stars—stars whose brightness changes over time, slowly shifting between brilliant and dim—when, in 1912, Henrietta Leavitt announced a remarkable (and totally unanticipated) discovery about them. For these stars, the length of time between their brightest and dimmest points seemed to be related to their overall brightness: slower cycling stars are more luminous. At the time, no one knew why that was the case, but nevertheless, the discovery allowed astronomers to infer the distances to far-off stars, and hence, to figure out the size of our own galaxy. Leavitt's observation was a true surprise—a discovery in the classic sense—but one that came only after she'd spent years carefully comparing thousands of photos of these specks of light, looking for patterns in the darkness.

The process of scientific discovery is not limited to professional scientists working in labs. The everyday experience of deducing that your car won't start because of a bad fuel pump, or of figuring out that the centipedes in your backyard prefer shady rocks shares fundamental similarities with classically scientific discoveries like working out DNA's double helix. These activities all involve making observations and analyzing evidence—and they all provide the satisfaction of finding an answer that makes sense of all the facts. In fact, some psychologists argue that the way individual humans learn (especially as children) bears a lot of similarity to the progress of science: both involve making observations, considering evidence, testing ideas, and holding on to those that work.

Photo of Henrietta Leavitt provided by the American Association of Variable Star Observers (AAVSO).

Understanding Science

A science checklist

So what, exactly, is science? Well, science turns out to be difficult to define precisely. (Philosophers have been arguing about it for decades!) The problem is that the term *"science"* applies to a remarkably broad set of human endeavors, from developing lasers, to analyzing the factors that affect human decision-making.

To get a grasp on what science is, we'll look at a checklist that summarizes key characteristics of science and compare it to a prototypical case of science in action: Ernest Rutherford's investigation into the structure of the atom. Then, we'll look at some other cases that are less "typical" examples of science to see how they measure up and what characteristics they share.

This checklist provides a guide for what sorts of activities are encompassed by science, but since the boundaries of science are not clearly defined, the list should not be interpreted as all-or-nothing. Some of these characteristics are particularly important to science (e.g., all of science must ultimately rely on evidence), but others are less central. For example, some perfectly scientific investigations may run into a dead end and not lead to ongoing research. Use this checklist as a reminder of the usual features of science. If something doesn't meet most of these characteristics, it shouldn't be treated as science.

Science checklist:
How scientific is it?

- [x] Focuses on the natural world
- [ ] Aims to explain the natural world
- [ ] Uses testable ideas
- [ ] Relies on evidence
- [ ] Involves the scientific community
- [ ] Leads to ongoing research
- [ ] Benefits from scientific behavior

Science asks questions about the natural world

Science studies the natural world. This includes the components of the physical universe around us like atoms, plants, ecosystems, people, societies and galaxies, as well as the natural forces at work on those things. In contrast, science cannot study supernatural forces and explanations. For example, the idea that a supernatural afterlife exists is not a part of science since this afterlife operates outside the rules that govern the natural world.

Anything in the natural world—from exotic ecosystems to urban smog—can be the subject of scientific inquiry.

Cococino National Forest photo by Gerald and Buff Corsi © California Academy of Sciences; Jupiter photo by NASA/JPL/Space Science Institute; photo of smoggy skyline by EPA; fungus photo by Dr. Robert Thomas and Dorothy B. Orr © California Academy of Sciences.

Understanding Science

Science can investigate all sorts of questions:

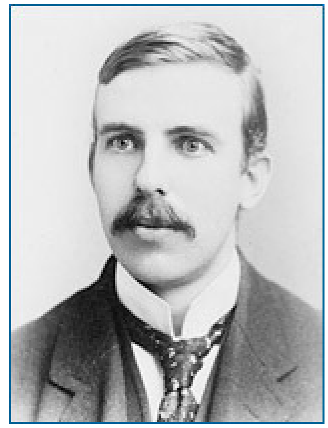
- When did the oldest rocks on earth form?
- Through what chemical reactions do fungi get energy from the nutrients they absorb?
- What causes Jupiter's red spot?
- How does smog move through the atmosphere?

Very few questions are off-limits in science—but the sorts of answers science can provide are limited. Science can only answer in terms of natural phenomena and natural processes. When we ask ourselves questions like, What is the meaning of life? and Does the soul exist? we generally expect answers that are outside of the natural world—and hence, outside of science.

A SCIENCE PROTOTYPE: RUTHERFORD AND THE ATOM

In the early 1900s, Ernest Rutherford studied (among other things) the organization of the atom—the fundamental particle of the natural world. Though atoms cannot be seen with the naked eye, they can be studied with the tools of science since they are part of the natural world.

Rutherford's story continues as we examine each item on the Science Checklist. To find out how this investigation measures up against the rest of the checklist, read on.



Ernest Rutherford

Rutherford photo from the Library of Congress.

Understanding Science

Science aims to explain and understand

Science checklist:
How scientific is it?

- [x] Focuses on the natural world
- [x] Aims to explain the natural world
- [ ] Uses testable ideas
- [ ] Relies on evidence
- [ ] Involves the scientific community
- [ ] Leads to ongoing research
- [ ] Benefits from scientific behavior

Science as a collective institution aims to produce more and more accurate natural explanations of how the natural world works, what its components are, and how the world got to be the way it is now. Classically, science's main goal has been building knowledge and understanding, regardless of its potential applications—for example, investigating the chemical reactions that an organic compound undergoes in order to learn about its structure. However, increasingly, scientific research is undertaken with the explicit goal of solving a problem or developing a technology, and along the path to that goal, new knowledge and explanations are constructed. For example, a chemist might try to produce an antimalarial drug synthetically and in the process, discover new methods of forming bonds that can be applied to making other chemicals. Either way (so-called *"pure"* or *"applied"* research), science aims to increase our understanding of how the natural world works.

A coelacanth

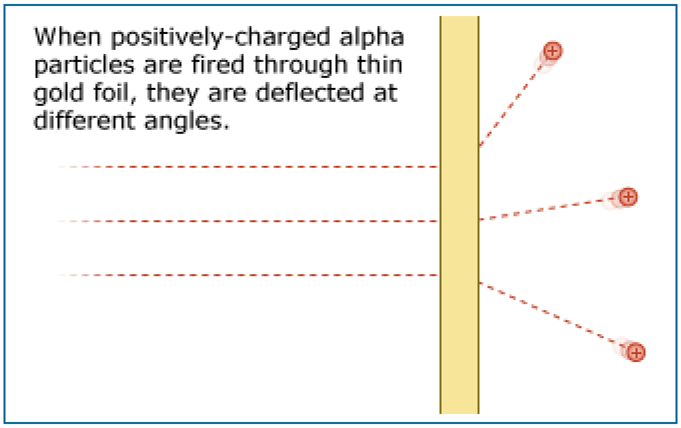
The knowledge that is built by science is always open to question and revision. No scientific idea is ever once-and-for-all "proved." Why not? Well, science is constantly seeking new evidence, which could reveal problems with our current understandings. Ideas that we fully accept today may be rejected or modified in light of new evidence discovered tomorrow. For example, up until 1938, paleontologists accepted the idea that coelacanths (an ancient fish) went extinct at the time that they last appear in the fossil record—about 80 million years ago. But that year, a live coelacanth was discovered off the coast of South Africa, causing scientists to revise their ideas and begin to investigate how this animal survives in the deep sea.

Despite the fact that they are subject to change, scientific ideas are reliable. The ideas that have gained scientific acceptance have done so because they are supported by many lines of evidence. These scientific explanations continually generate expectations that hold true, allowing us to figure out how entities in the natural world are likely to behave (e.g., how likely it is that a child will inherit a particular genetic disease) and how we can harness that understanding to solve problems (e.g., how electricity, wire, glass, and various compounds can be fashioned into a working light bulb). For example, scientific understandings of motion and gases allow us to build airplanes that reliably get us from one airport to the next. Though the knowledge used to design airplanes is technically provisional, time and time again, that knowledge has allowed us to produce airplanes that fly. We have good reason to trust scientific ideas: they work!

Understanding Science

A SCIENCE PROTOTYPE: RUTHERFORD AND THE ATOM

Ernest Rutherford's investigations were aimed at understanding a small, but illuminating, corner of the natural world: the atom. He investigated this world using alpha particles, which are helium atoms stripped of their electrons. Rutherford had found that when a beam of these tiny, positively-charged alpha particles is fired through gold foil, the particles don't stay on their beeline course, but are deflected (or "scattered") at different angles. Rutherford wanted to figure out what this might tell him about the layout of an atom.



Rutherford's story continues as we examine each item on the Science Checklist. To find out how this investigation measures up against the rest of the checklist, read on.

Understanding Science

Science works with testable ideas

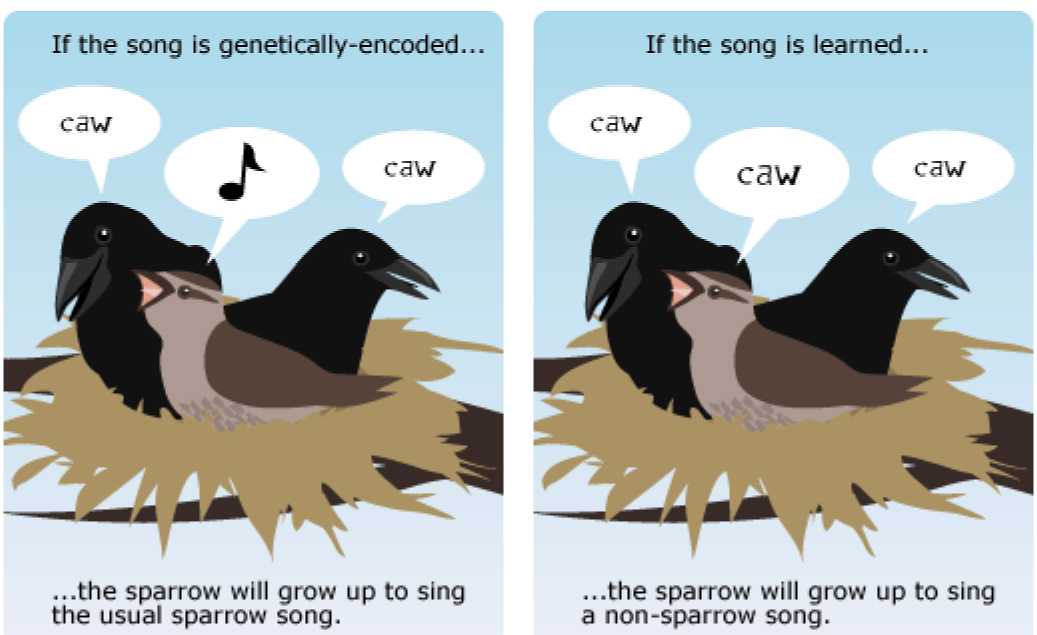
Science checklist:
How scientific is it?

- [x] Focuses on the natural world
- [x] Aims to explain the natural world
- [x] Uses testable ideas
- [ ] Relies on evidence
- [ ] Involves the scientific community
- [ ] Leads to ongoing research
- [ ] Benefits from scientific behavior

Only testable ideas are within the purview of science. For an idea to be testable, it must logically generate specific expectations—in other words, a set of observations that we could expect to make if the idea were true and a set of observations that would be inconsistent with the idea and lead you to believe that it is not true. For example, consider the idea that a sparrow's song is genetically encoded and is unaffected by the environment in which it is raised, in comparison to the idea that a sparrow learns the song it hears as a baby. Logical reasoning about this example leads to a specific set of expectations. If the sparrow's song were indeed genetically encoded, we would expect that a sparrow raised in the nest of a different species would grow up to sing a sparrow song like any other member of its own species. But if, instead, the sparrow's song were learned as a chick, raising a sparrow in the nest of another species should produce a sparrow that sings a non-sparrow song. Because they generate different expected observations, these ideas are testable. A scientific idea may require a lot of reasoning to work out an appropriate test, may be difficult to test, may require the development of new technological tools to test, or may require one to make independently testable assumptions to test—but to be scientific, an idea must be testable, somehow, someway.

Question: Is a sparrow's song genetically-encoded or learned?

Test: See what happens when a sparrow is raised in the nest of another species.



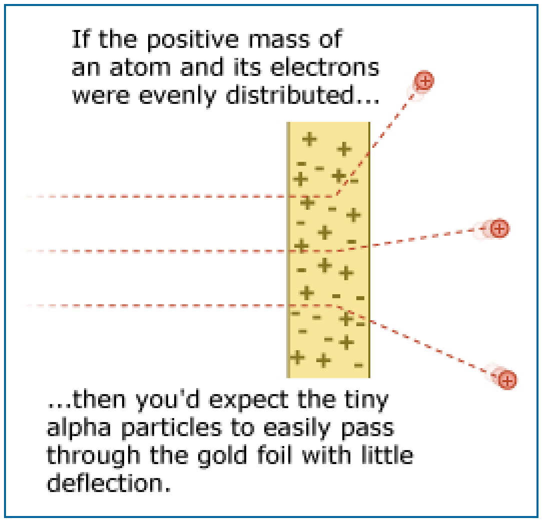
If an explanation is equally compatible with all possible observations, then it is not testable and hence, not within the reach of science. This is frequently the case with ideas about supernatural entities. For example, consider the idea that an all-powerful supernatural being controls our actions. Is there anything we could do to test that idea? No. Because this supernatural being is all-powerful, anything we observe could

Understanding Science

be chalked up to the whim of that being. Or not. The point is that we can't use the tools of science to gather any information about whether or not this being exists—so such an idea is outside the realm of science.

A SCIENCE PROTOTYPE: RUTHERFORD AND THE ATOM

Before 1910, Ernest Rutherford and many other scientists had the idea that the positive charge and the mass of an atom were evenly distributed throughout the whole atom, with electrons scattered throughout. You can imagine this model of the atom as a loosely packed snowball (the positive mass of the atom) with a few tiny grains of sand (the electrons) scattered throughout. The idea that atoms are arranged in this way can be tested by firing an alpha particle beam through a piece of gold foil. If the idea were correct, then the positive mass in the gold foil would be relatively diffuse (the loosely packed snow) and would allow the alpha particles to pass through the foil with only minor scattering.



Rutherford's story continues as we examine each item on the Science Checklist. To find out how this investigation measures up against the rest of the checklist, read on.

Science relies on evidence

Science checklist:
How scientific is it?

- [x] Focuses on the natural world
- [x] Aims to explain the natural world
- [x] Uses testable ideas
- [x] Relies on evidence
- [ ] Involves the scientific community
- [ ] Leads to ongoing research
- [ ] Benefits from scientific behavior

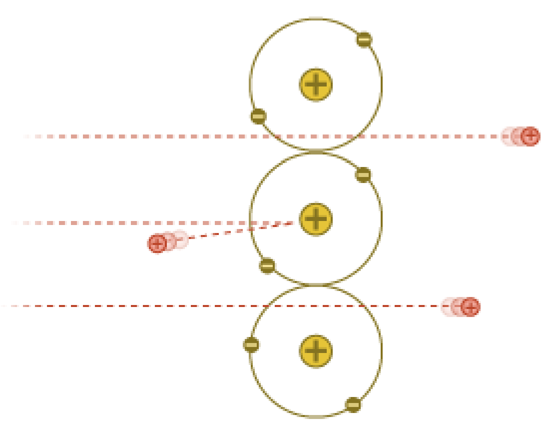
Ultimately, scientific ideas must not only be testable, but must actually be tested—preferably with many different lines of evidence by many different people. This characteristic is at the heart of all science. Scientists actively seek evidence to test their ideas—even if the test is difficult and means, for example, spending years working on a single experiment, traveling to Antarctica to measure carbon dioxide levels in an ice core, or collecting DNA samples from thousands of volunteers all over the world. Performing such tests is so important to science because in science, the acceptance or rejection of a scientific idea depends upon the evidence relevant to it—not upon dogma, popular opinion, or tradition. In science, ideas that are not supported by evidence are ultimately rejected. And ideas that are protected from testing or are only allowed to be tested by one group with a vested interest in the outcome are not a part of good science.

A SCIENCE PROTOTYPE: RUTHERFORD AND THE ATOM

Ernest Rutherford's lab tested the idea that an atom's positive mass is spread out diffusely by firing an alpha particle beam through a piece of gold foil, but the evidence resulting from that experiment was a complete surprise: most of the alpha particles passed through the gold foil without changing direction much as expected, but some of the alpha particles came bouncing back in the opposite direction, as though they had struck something dense and solid in the gold foil. If the gold atoms were really like loosely packed snowballs, all of the alpha particles should have passed through the foil, but they did not!

From this evidence, Rutherford concluded that their snowball model of the atom had been incorrect, even though it was popular with many other scientists. Instead, the evidence suggested that an atom is mostly empty space and that its positive charge is concentrated in a dense mass at its core, forming a nucleus. When the positively charged alpha particles were fired at the gold foil, most of them passed through the empty space of the gold atoms with little deflection, but a few of them ran smack into the dense, positively charged nucleus of a gold atom and were repelled straight back (like what would happen if you tried to make the north poles of two strong magnets touch). The idea that atoms have positively charged nuclei was also testable. Many independent experiments were performed by other researchers to see if the idea fit with other experimental results.

The observed deflection of alpha particles shows that atoms have their positive charge concentrated in a dense mass.



Rutherford's story continues as we examine each item on the Science Checklist. To find out how this investigation measures up against the rest of the checklist, read on.

Science is embedded in the scientific community

Science checklist:
How scientific is it?

- [x] Focuses on the natural world
- [x] Aims to explain the natural world
- [x] Uses testable ideas
- [x] Relies on evidence
- [x] Involves the scientific community
- [ ] Leads to ongoing research
- [ ] Benefits from scientific behavior

The progress of science depends on interactions within the scientific community—that is, the community of people and organizations that generate scientific ideas, test those ideas, publish scientific journals, organize conferences, train scientists, distribute research funds, etc. This scientific community provides the cumulative knowledge base that allows science to build on itself. It is also responsible for the further testing and scrutiny of ideas and for performing checks and balances on the work of community members.

In addition, much scientific research is collaborative, with different people bringing their specialized knowledge to bear on different aspects of the problem. For example, a 2006 journal article on regional variations in the human genome was the result of a collaboration between 43 people from the U.K., Japan, the U.S., Canada, and Spain! Even Charles Darwin, who initially investigated the idea of evolution through natural selection while living almost as a hermit at his country estate, kept up a lively correspondence with his peers, sending and receiving numerous letters dealing with his ideas and the evidence relevant to them.

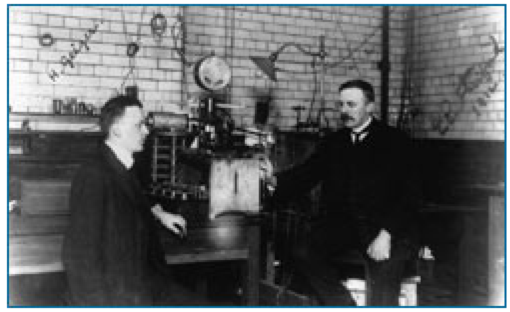
In rare cases, scientists do actually work in isolation. Gregor Mendel, for example, figured out the basic principles of genetic inheritance as a secluded monk with very little scientific interaction. However, even in such cases, research must ultimately involve the scientific community if that work is to have any impact on the progress of science. In Mendel's case, the ultimate involvement of the scientific community through his published work was critical because it allowed other scientists to evaluate those ideas independently, investigate new lines of evidence, and develop extensions of his ideas. This community process may be chaotic and slow, but it is also crucial to the progress of science.

Scientists sometimes work alone and sometimes work together, but communication within the scientific community is always important.

Understanding Science

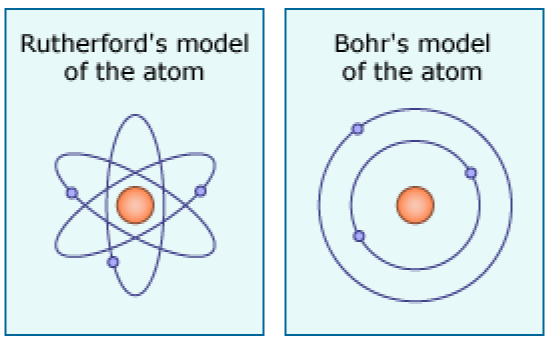
A SCIENCE PROTOTYPE: RUTHERFORD AND THE ATOM

Though Ernest Rutherford came up with the idea that atoms have positively charged nuclei, the research that led to this idea was a collaborative effort: Rutherford was assisted by Hans Geiger, and the critical alpha-scattering experiment was actually carried out by Ernest Marsden, an undergraduate student working in Rutherford's lab.



Ernest Rutherford (right) and Hans Geiger in the physics laboratory at Manchester University, England, circa 1912. Permission of the Alexander Turnbull Library, Wellington, New Zealand, must be obtained before any re-use of this image. Reference number: PAColl-0091-1-011.

Furthermore, after his discovery of the layout of the atom, Rutherford published a description of the idea and the relevant evidence, releasing it to the scientific community for scrutiny and evaluation. And scrutinize they did. Niels Bohr noticed a problem with Rutherford's idea: there was nothing keeping the orbiting electrons from spiraling into the nucleus of the atom, causing the whole thing to collapse! Bohr modified Rutherford's basic model by proposing that electrons had set energy levels, which helped solve the problem and earned Bohr a Nobel Prize. Since then, many other scientists have built on and modified Bohr's model.



Lithium atoms, diagrammed in the Rutherford and Bohr models. Rutherford's model does not differentiate between any of the electrons, while Bohr's places electrons into orbits with set energy levels.

Rutherford's story continues as we examine each item on the Science Checklist. To find out how this investigation measures up against the rest of the checklist, read on.

Understanding Science

Scientific ideas lead to ongoing research

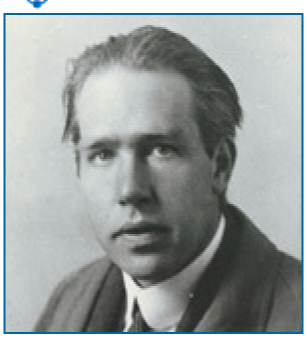
Science checklist:
How scientific is it?

- [x] Focuses on the natural world
- [x] Aims to explain the natural world
- [x] Uses testable ideas
- [x] Relies on evidence
- [x] Involves the scientific community
- [x] Leads to ongoing research
- [ ] Benefits from scientific behavior

Science is an ongoing endeavor. It did not end with the most recent edition of your college physics textbook and will not end even once we know the answers to big questions, such as how our 20,000 genes interact to build a human being or what dark matter is. So long as there are unexplored and unexplained parts of the natural world, science will continue to investigate them.

Most typically in science, answering one question inspires deeper and more detailed questions for further research. Similarly, coming up with a fruitful idea to explain a previously anomalous observation frequently leads to new expectations and areas of research. So, in a sense, the more we know, the more we know what we don't yet know. As our knowledge expands, so too does our awareness of what we don't yet understand. For example, James Watson and Francis Crick's proposal that DNA takes the form of a double helix helped answer a burning question in biology about the chemical structure of DNA. And while it helped answer one question, it also generated new expectations (e.g., that DNA is copied via base pairing), raised many new questions (e.g., how does DNA store information?), and contributed to whole new fields of research (e.g., genetic engineering). Like Watson and Crick's work, most scientific research generates new expectations, inspires new questions, and leads to new discoveries.

A SCIENCE PROTOTYPE: RUTHERFORD AND THE ATOM


Niels Bohr

Niels Bohr built upon Ernest Rutherford's work to develop the model of the atom most commonly portrayed in textbooks: a nucleus orbited by electrons at different levels. Despite the new questions it raised (e.g., how do orbiting electrons avoid violating the rules of electricity and magnetism when they don't spiral into the nucleus?), this model was powerful and, with further modification, led to a wide range of accurate predictions and new discoveries: from predicting the outcome of chemical reactions, to determining the composition of distant stars, to conceiving of the atomic bomb.

Rutherford's story continues as we examine each item on the Science Checklist. To find out how this investigation measures up to the last item of the checklist, read on.

Participants in science behave scientifically

Science checklist:
How scientific is it?

- ☑ Focuses on the natural world
- ☑ Aims to explain the natural world
- ☑ Uses testable ideas
- ☑ Relies on evidence
- ☑ Involves the scientific community
- ☑ Leads to ongoing research
- ☑ Benefits from scientific behavior

Science is sometimes misconstrued as an elite endeavor in which one has to be a member of "the club" in order to be taken seriously. That's a bit misleading. In fact, science is now open to anyone (regardless of age, gender, religious commitment, physical ability, ethnicity, country of origin, political views, nearsightedness, favorite ice cream flavor—whatever!) and benefits tremendously from the expanding diversity of perspectives offered by its participants. However, science only works because the people involved with it behave "scientifically"—that is, behave in ways that push science forward.

But what exactly does one have to do to behave scientifically? Here is a scientist's code of conduct:

1) **Pay attention to what other people have already done.** Scientific knowledge is built cumulatively. If you want to discover exciting new things, you need to know what people have already discovered before you. This means that scientists study their fields extensively to understand the current state of knowledge.

2) **Expose your ideas to testing.** Strive to describe and perform the tests that might suggest you are wrong and/or allow others to do so. This may seem like shooting yourself in the foot but is critical to the progress of science. Science aims to accurately understand the world, and if ideas are protected from testing, it's impossible to figure out if they are accurate or inaccurate!

3) **Assimilate the evidence.** Evidence is the ultimate arbiter of scientific ideas. Scientists are not free to ignore evidence. When faced with evidence

contradicting his or her idea, a scientist may suspend judgment on that idea pending more tests, may revise or reject the idea, or may consider alternate ways to explain the evidence, but ultimately, scientific ideas are sustained by evidence and cannot be propped up if the evidence tears them down.

4) **Openly communicate ideas and tests to others.** Communication is important for many reasons. If a scientist keeps knowledge to her- or himself, others cannot build upon those ideas, double-check the work, or devise new ways to test the ideas.

5) **Play fair: Act with scientific integrity.** Hiding evidence, selectively reporting evidence, and faking data directly thwart science's main goal—to construct accurate knowledge about the natural world. Hence, maintaining high standards of honesty, integrity, and objectivity is critical to science.

A SCIENCE PROTOTYPE: RUTHERFORD AND THE ATOM

Ernest Rutherford and his colleagues acted in ways that moved science forward:

- They understood the relevant knowledge in their field. Rutherford had studied physics for more than 20 years when he proposed the idea of the nucleus.
- They exposed their ideas to testing. Even though his original view of the atom suggested that no backscattering should occur, Rutherford decided to look for backscattered alpha particles anyway, just to be thorough.
- They assimilated the evidence. When their experimental results did not support the "snowball" model of the atom, instead of writing those results off as an anomaly, they modified their original ideas in light of the new evidence.
- They openly communicated their ideas so that other physicists could test them as well. Rutherford published the experimental results, a description of his reasoning, and the idea of the nucleus in 1911 in a scientific journal.
- They acted with scientific integrity. In his paper on the topic, Rutherford assigned credit fairly (citing the contributions of his colleagues, Geiger and Marsden) and reported his results honestly—even when experimental results and his theoretical calculations did not match up perfectly.

The scientists involved with this investigation lived up to the five points in the scientist's code of conduct. In this way—and judging by the other items on the Science Checklist—this investigation of atomic structure is well within the purview of science.

Understanding Science

Beyond physics, chemistry, and biology

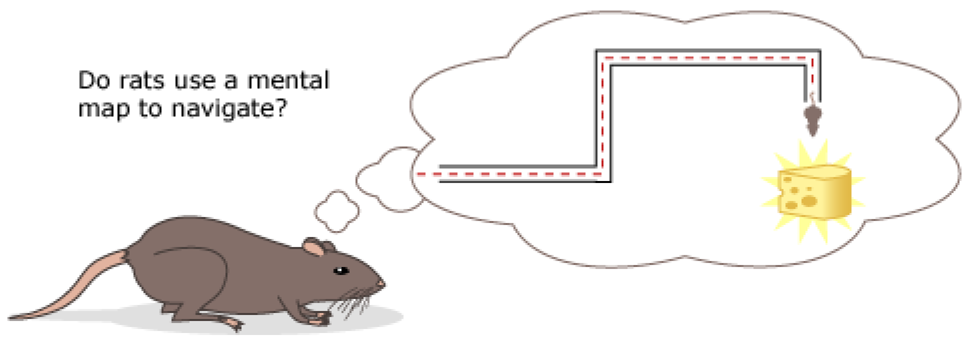
Science checklist:
How scientific is it?

- ☑ Focuses on the natural world
- ☑ Aims to explain the natural world
- ☑ Uses testable ideas
- ☑ Relies on evidence
- ☑ Involves the scientific community
- ☑ Leads to ongoing research
- ☑ Benefits from scientific behavior

We've seen that scientific research generally meets a set of key characteristics: it focuses on improving our understanding of the natural world, works with testable ideas that can be verified with evidence, relies on the scientific community, inspires ongoing research, and is performed by people who behave scientifically. While not all scientific investigations line up perfectly with the Science Checklist, science, as an endeavor, strives to embody these features. Ernest Rutherford's discovery of the atomic nucleus, for example, satisfied those characteristics quite neatly. But how would a less stereotypically "scientific" investigation—one that wouldn't show up in a high school science textbook—measure up against the Science Checklist? To find out, we'll look at an example from the field of psychology …

Beyond the prototype: Animal psychology

Most of us have probably wondered how other animals think and experience the world (e.g, is Fido really happy to see me or does he just want a treat?)—but can that curiosity be satisfied by science? After all, how could we ever test an idea about how another animal thinks? In the 1940s, psychologist Edward Tolman investigated a related question using the methods of science. He wanted to know how rats successfully navigate their surroundings—for example, a maze containing a hidden reward. Tolman suspected that rats would build mental maps of the maze as they investigated it (forming a mental picture of the layout of the maze), but many of his colleagues thought that rats would learn to navigate the maze through stimulus-response, associating particular cues with particular outcomes (e.g., taking this tunnel means I get a piece of cheese) without forming any big picture of the maze.



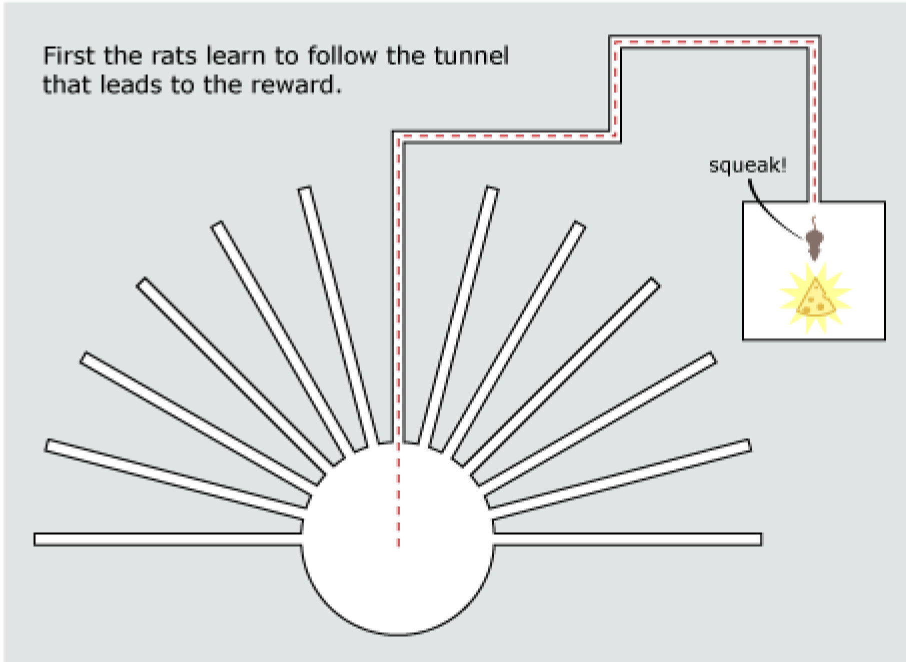
Here's how Tolman's investigation measures up against our checklist:

☑ **Natural world?**
The brains of rats and their workings are a part of the natural world, as is the behavior of rats.

☑ **Aims to explain?**
Tolman aimed to explain how rats navigate their surroundings.

☑ **Testable ideas?**
The two ideas about how rats navigate (mental maps vs. stimulus-response) are testable, but figuring out how to test them required some clever and logical thinking about experimental design. To test these ideas, Tolman and his colleagues trained rats in a maze which offered them many different tunnels to enter first. One of the tunnels

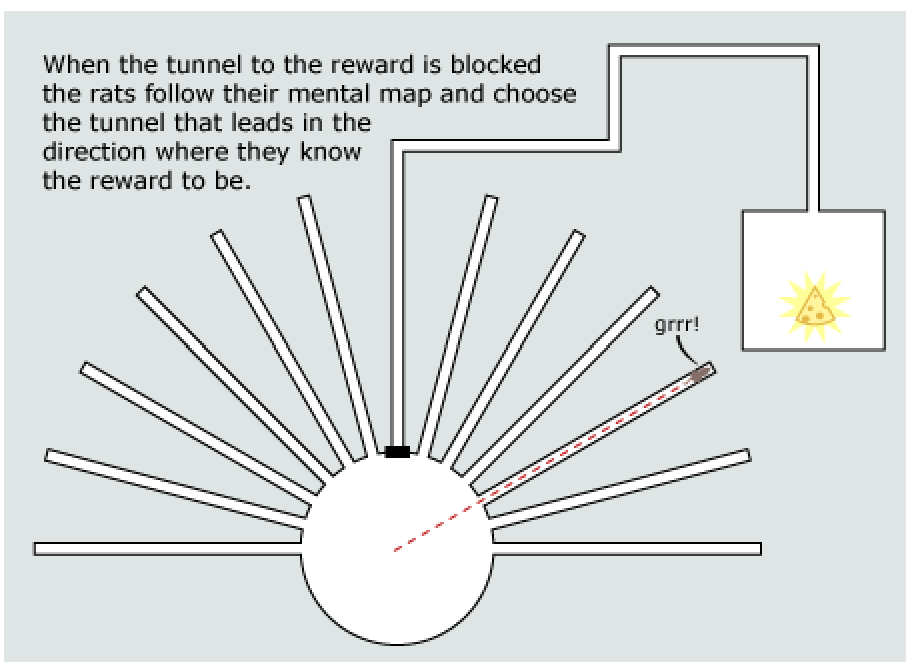
Understanding Science



twisted and turned but consistently led to the reward, and the rats quickly learned to go down that tunnel. Then the experimenters blocked the entrance to the reward tunnel. What would the rats do? Tolman reasoned that if the rats were navigating with a mental map, they would pick another tunnel that, according to their mental map of the maze, led in the direction of the food. But if the rats were navigating via stimulus-response, Tolman reasoned that they would choose the tunnel closest to the original reward tunnel, regardless of where it led, since that was closest to the stimulus with the pay-off.

Relies on evidence?

Tolman and his colleagues tested the mental map idea with several experiments, including the tunnel experiment described above. In that experiment, they found that most of the rats picked a tunnel that led in the direction of the food, instead of one close to the original reward tunnel. The evidence supported the idea that rats navigate using something like a mental map.



Understanding Science

☑ Scientific community?
Tolman published many papers on this topic in scientific journals in order to explain his experiments and the evidence relevant to them to other psychologists.

☑ Ongoing research?
This research is a small part of a much larger body of ongoing psychological research about how organisms learn and make decisions based on their representations of the world.

☑ Scientific behavior?
Edward Tolman and his colleagues acted with scientific integrity and behaved in ways that push science forward. They accurately reported their results and allowed others to test their ideas.

Understanding Science

Science in disguise

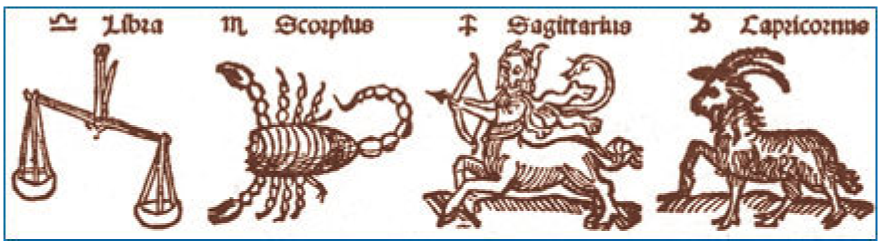
Teaching is an example of a challenge that can be addressed by science.

Our Science Checklist fits well with a wide range of investigations—from developing an Alzheimer's drug, to dissecting the structure of atoms, to probing the neurology of human emotion. Even endeavors far from one's typical picture of science, like figuring out how best to teach English as a second language or examining the impact of a government deficit on the economy, can be addressed by science.

Disguised as science

However, other human endeavors, which might at first seem like science, are actually not very much like science at all. For example, the Intelligent Design movement promotes the idea that many aspects of life are too complex to have evolved without the intervention of an intelligent cause—assumed by most proponents to be a supernatural being, like God. Promoters of this idea are interested in explaining what we observe in the natural world (the features of living things), which does align well with the aims of science. However, because Intelligent Design relies on the action of an unspecified "intelligent cause," it is not a testable idea. Furthermore, the movement itself has several other characteristics that reveal it to be non-science.

Western astrology aims to explain and predict events on Earth in terms of the positions of the sun, planets, and constellations; hence, like science, astrology focuses on explaining the natural world. However, in many other ways, astrology is not much like science at all.



Western astrology is not science.

Understanding Science

Science has limits: A few things that science does not do

Science is powerful. It has generated the knowledge that allows us to call a friend halfway around the world with a cell phone, vaccinate a baby against polio, build a skyscraper, and drive a car. And science helps us answer important questions like which areas might be hit by a tsunami after an earthquake, how did the hole in the ozone layer form, how can we protect our crops from pests, and who were our evolutionary ancestors? With such breadth, the reach of science might seem to be endless, but it is not. Science has definite limits.

Science doesn't make moral judgments

When is euthanasia the right thing to do? What universal rights should humans have? Should other animals have rights? Questions like these are important, but scientific research will not answer them. Science can help us learn about terminal illnesses and the history of human and animal rights—and that knowledge can inform our opinions and decisions. But ultimately, individual people must make moral judgments. Science helps us describe how the world is, but it cannot make any judgments about whether that state of affairs is right, wrong, good, or bad.

Science doesn't make aesthetic judgments

Science can reveal the frequency of a G-flat and how our eyes relay information about color to our brains, but science cannot tell us whether a Beethoven symphony, a Kabuki performance, or a Jackson Pollock painting is beautiful or dreadful. Individuals make those decisions for themselves based on their own aesthetic criteria.

Science doesn't tell you how to use scientific knowledge

Although scientists often care deeply about how their discoveries are used, science itself doesn't indicate what should be done with scientific knowledge. Science, for example, can tell you how to recombine DNA in new ways, but it doesn't specify whether you should use that knowledge to correct a genetic disease, develop a bruise-resistant apple, or construct a new bacterium. For almost any important scientific advance, one can imagine both positive and negative ways that knowledge could be used. Again, science helps us describe how the world is, and then we have to decide how to use that knowledge.

Science doesn't draw conclusions about supernatural explanations

Do gods exist? Do supernatural entities intervene in human affairs? These questions may be important, but science won't help you answer them. Questions that deal with supernatural explanations are, by definition, beyond the realm of nature—and hence, also beyond the realm of what can be studied by science. For many, such

Understanding Science

questions are matters of personal faith and spirituality.

Moral judgments, aesthetic judgments, decisions about applications of science, and conclusions about the supernatural are outside the realm of science, but that doesn't mean that these realms are unimportant. In fact, domains such as ethics, aesthetics, and religion fundamentally influence human societies and how those societies interact with science. Neither are such domains unscholarly. In fact, topics like aesthetics, morality, and theology are actively studied by philosophers, historians, and other scholars. However, questions that arise within these domains generally cannot be resolved by science.

Understanding Science

Science in sum

In this section, we've seen that, though hard to define concisely, science has a handful of key features that set it apart from other areas of human knowledge. However, the net cast by science is wide. The Science Checklist matches up to a diverse set of human endeavors—from uncovering the fundamental particles of the universe, to studying the mating behavior of lobsters, to investigating the effects of different economic policies. We've also seen that science has limits: some questions that are an important part of the human experience are not answerable within the context of science.

So science isn't everything, but it is important. Science helps us construct knowledge about the natural world—knowledge that can then be harnessed to improve our lives and solve problems. How does science do it? To find out, read on …