# Understanding Evolution: Nature of Science

Understanding how science works allows one to easily distinguish science from non-science. Thus, to understand biological evolution, or any other science, it is essential to begin with the nature of science.

## What is Science?

Fossil image courtesy of Diane Erwin, UCMP.

Science is a particular way of understanding the natural world. It extends the intrinsic curiosity with which we are born. It allows us to connect the past with the present, as with the redwoods depicted here.

Science is based on the premise that our senses, and extensions of those senses through the use of instruments, can give us accurate information about the Universe. Science follows very specific "rules" and its results are always subject to testing and, if necessary, revision. Even with such constraints science does not exclude, and often benefits from, creativity and imagination (with a good bit of logic thrown in).

## Science Asks Three Basic Questions

1. **What's there?**
   The astronaut picking up rocks on the moon, the nuclear physicist bombarding atoms, the marine biologist describing a newly discovered species, the paleontologist digging in promising strata, are all seeking to find out, "What's there?"
2. **How does it work?**
   A geologist comparing the effects of time on moon rocks to the effects of time on earth rocks, the nuclear physicist observing the behavior of particles, the marine biologist observing whales swimming, and the paleontologist studying the locomotion of an extinct dinosaur, "How does it work?"
3. **How did it come to be this way?**
   Each of these scientists tries to reconstruct the histories of their objects of study. Whether these objects are rocks, elementary particles, marine organisms, or fossils, scientists are asking, "How did it come to be this way?"

### Science Works in Specific Ways

The purpose of science is to learn about our universe. The joy of science emanates from the freedom to explore and wonder. However, in order to maximize the probability that in the end we get things right, science follows sensible guidelines. It is important to keep in mind certain fundamentals:

- Science relies on evidence from the natural world and this evidence is examined and interpreted through logic.
- Creative flexibility is essential to scientific thinking, however science follows a process guided by certain parameters.
- Science is embedded within the culture of its times.

Understanding how science works allows one to easily distinguish science from non-science.

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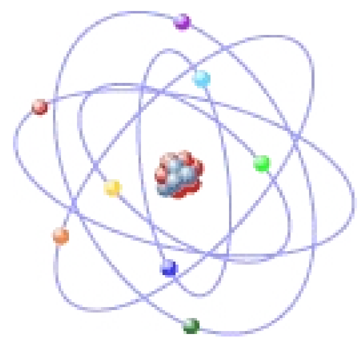
## Science Has Principles

Science seeks to explain the natural world and its explanations are tested using evidence from the natural world. Birds and lizards are known to exist in nature and therefore fall within the scope of science.

Elves and gnomes are great fun to read about and even to enjoy as statues in our gardens, but they do not dwell in the natural world. That means they are not appropriate for scientific study. The basis of any scientific understanding is information gleaned from observations of nature.

Science assumes that we can learn about the natural world by gathering evidence through our senses and extensions of our senses. A flower or a rock can be directly observed with no special aids. But using technology, we can expand the realm of human senses to observe such invisible phenomena as electricity and magnetic fields, and objects such as bacteria and faraway galaxies. Dreams, apparitions and hallucinations, on the other hand, may seem real but they do not arise from our senses and are not even extensions of our senses. The ultimate test of any conceptual understanding exists only in real materials and observations. Evidence is the basic stuff of science. Without evidence there is only speculation.

## Science Is a Process, Part 1



Scientific ideas are developed through reasoning. Inferences are logical conclusions based on observable facts. Much of what we know from scientific study is based on inferences from data, whether the object of study is a star or an atom. No person has ever seen inside an atom, yet we know, by inference, what is there. Atoms have been disassembled and their components determined. The history of life on Earth has likewise been inferred through multiple lines of evidence.

Scientific claims are based on testing explanations against observations of the natural world and rejecting the ones that fail the test.

Scientific explanations are evaluated using evidence from the natural world. That evidence may come from various sources: a controlled lab experiment, a study of anatomy, or recordings of radiation from outerspace, to name just a few. Explanations that don't fit the evidence are rejected or are modified and tested again.

Scientific claims are subject to peer review and replication.

Peer review is an integral part of genuine scientific enterprise and goes on continuously in all areas of science. The process of peer review includes examination of other scientists' data and logic. It attempts to identify alternative explanations, and attempts to replicate observations and experiments.

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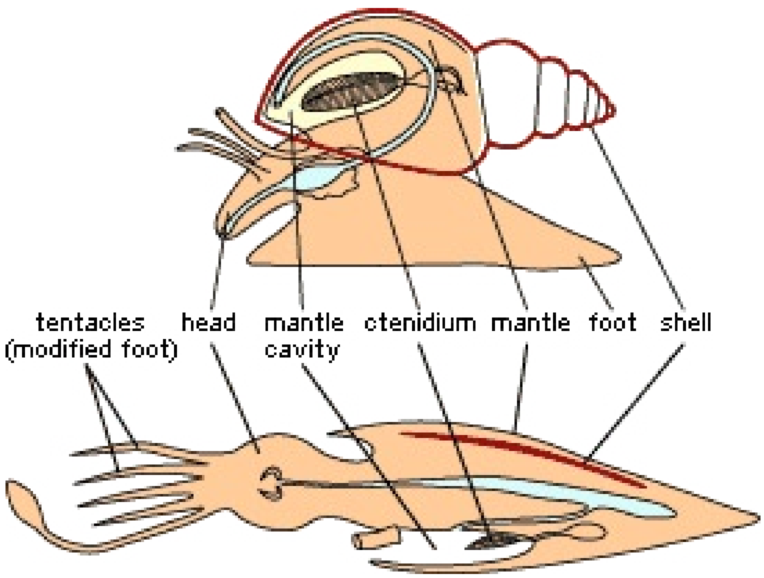
## Science Is a Process, Part 2

In the marketplace of ideas, the simplest explanation has the advantage. This principle is referred to as parsimony.

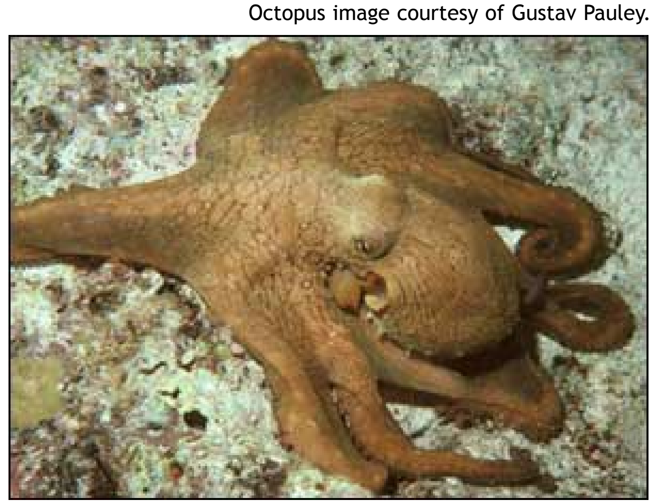
Consider these observations:

- A close look at snails, nautiloids, squids, octopi and cuttlefish reveals the basic similarity of the body form of each (see below).
- The shell of a nautilus and its extinct relatives, the ammonites, is very similar to the shell of a snail.
- The tentacles of an octopus, when carefully examined, can be seen to be a modified snail's foot.
- The stomachs of all members of this group have the same arrangement of parts.




One possible explanation is that these animals have independently acquired equivalent organs through a remarkable series of coincidences, but the most likely explanation is that these animals inherited similar organs through common ancestry. That is parsimony.

Octopus image courtesy of Gustav Pauley.



Common ancestry is the parsimonious explanation for the similarities between this octopus and its kin.

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## Science Is a Process, Part 3

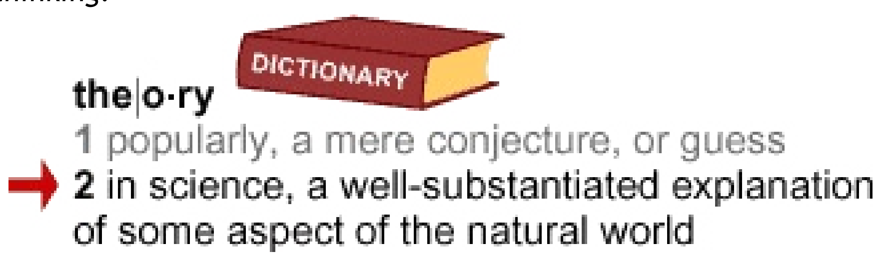
*There is no such thing as "THE Scientific Method."*
If you go to science fairs or read scientific journals, you may get the impression that science is nothing more than "question-hypothesis-procedure-data-conclusions."

But this is seldom the way scientists actually do their work. Most scientific thinking, whether done while jogging, in the shower, in a lab, or while excavating a fossil, involves continuous observations, questions, multiple hypotheses, and more observations. It seldom "concludes" and never "proves."

Putting all of science in the "Scientific Method" box, with its implication of a white-coated scientist and bubbling flasks, misrepresents much of what scientists spend their time doing. In particular, those who are involved in historical sciences work in a very different way—one in which questioning, investigating, and hypothesizing can occur in any order.

## Science Is a Process, Part 4

*Theories are central to scientific thinking.*
Theories are overarching explanations that make sense of some aspect of nature, are based on evidence, allow scientists to make valid predictions, and have been tested in many ways. Theories are supported, modified, or replaced as new evidence appears. Theories give scientists frameworks within which to work. Major theories of science, such as the cell theory, gravitational theory, evolutionary theory, and particle theory, are all big ideas within which scientists test specific hypotheses.




The scientific definition of "theory" should not be confused with the way the term is commonly used to mean a guess or a hunch. In science, a theory means much more and is far more well-founded. The "Theory of Evolution" is an evidence-based, internally consistent, well-tested explanation of how the history of life proceeded on Earth—not a hunch. Understanding the role of theory in science is essential to scientists and vital to the informed citizen.

## Characteristics of Science, Part 1

*Conclusions of science are reliable, though tentative.*
Science is always a work in progress, and its conclusions are always tentative. But just as the word "theory" means something special to the scientist, so too does the word "tentative." Science's conclusions are not tentative in the sense that they are temporary until the real answer comes along. Scientific conclusions are well founded in their factual content and thinking and are tentative only in the sense that all ideas are open to scrutiny. In science, the tentativeness of ideas such as the nature of atoms, cells, stars or the history of the Earth refers to the willingness of scientists to modify their ideas as new evidence appears.

*Science is not democratic.*
Scientific ideas are subject to scrutiny from near and far, but nobody ever takes a vote. If the question of plate tectonics had been decided democratically when it was first presented in the early twentieth century, we would, today, have no explanation for the origins of much of Earth's terrain. Scientific ideas are accepted or rejected instead on the basis of evidence.

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## Characteristics of Science, Part 2

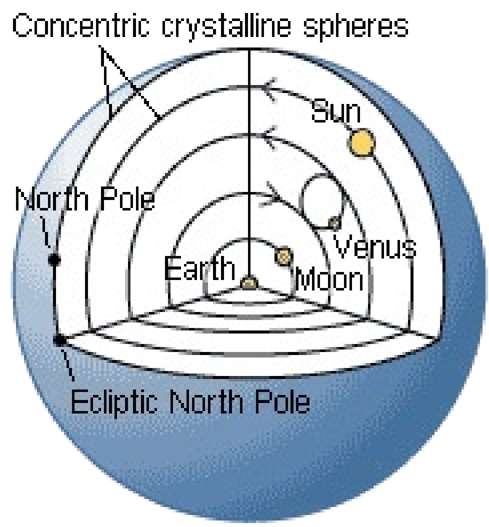
*Science is non-dogmatic.*
Nothing in the scientific enterprise or literature requires belief. To ask someone to accept ideas purely on faith, even when these ideas are expressed by "experts," is unscientific. While science must make some assumptions, such as the idea that we can trust our senses, explanations and conclusions are accepted only to the degree that they are well founded and continue to stand up to scrutiny.

*Science cannot make moral or aesthetic decisions.*
Scientists can infer the relationships of flowering plants from their anatomy, DNA, and fossils, but they cannot scientifically assert that a rose is prettier than a daisy. Being human, scientists make moral and aesthetic judgments and choices, as do all citizens of our planet, but such decisions are not part of science.

## Science Exists in a Cultural Context, Part 1

*Science is not always a direct ascent toward the truth.*
Despite the meticulous efforts of those who practice it, science sometimes proceeds in lurches and false starts. In some cases, scientific ideas that dominated a particular time were later recognized as inaccurate or incomplete.

- Before Galileo challenged the system, geocentrism was the rule. The geocentric model of the Universe, shown to the right, persisted for centuries. Eventually, people came to accept that the Earth is not the center of the Universe.
- Speciation was first described as a gradual process, but in recent years it has become clear that under some conditions speciation can occur relatively rapidly.
- Alfred Wegener's ideas about continental drift were not taken seriously until viable mechanisms for moving continents began to be recognized.

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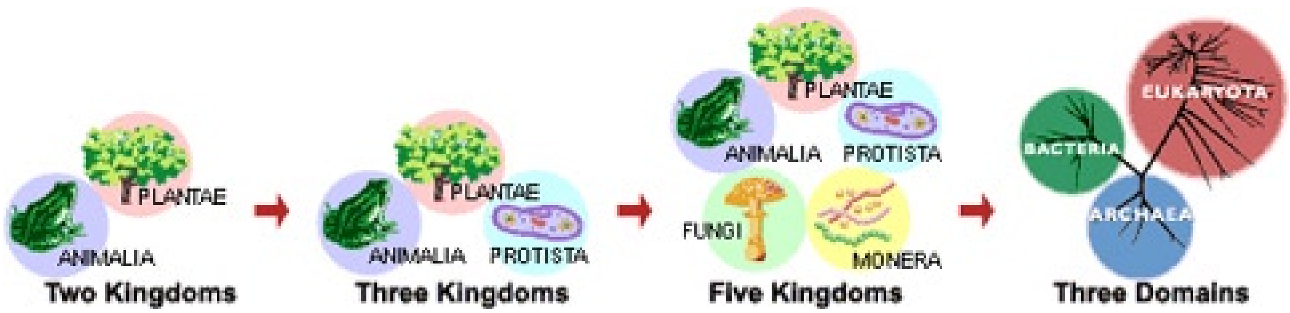
## Science Exists in a Cultural Context, Part 2

*Science corrects itself.*
Sometimes people make mistakes. Occasionally scientists are swept up in a current of ideas that leads them astray. But errors, misconceptions, and misdirections are corrected by the scientific community itself. Sometimes corrections take years, decades, or even centuries. Improved understanding may result from new technology or changing perspectives, but sooner or later a closer approximation of the truth appears. The fact that old hypotheses fall and new ones take their place does not mean that science is invalid as a way of gathering knowledge. Plasticity of thought is the very essence of the scientific process.

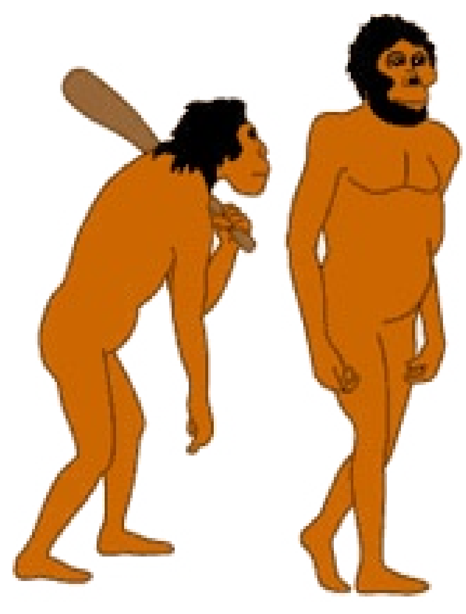
For example, within the past 100 years, textbooks have gone from grouping all living things into two kingdoms, to portraying the connectedness of life as three domains.




## Science Exists in a Cultural Context, Part 3

*Science is a human endeavor.*
All human frailties are present among scientists. These include:

- Falling in love with one's own hypothesis and becoming so attached to it that one refuses to consider new or conflicting data. The cold fusion episode of the 1990s, which implied unlimited energy from a low-temperature version of hydrogen fusion, should serve as a warning to would-be instant scientific heroes.
- *Being drawn in by preconceptions*
  A century ago people visualized the human ancestor with bent legs, club in hand, but with enough gray matter to make tools and control fire. "Cave man" cartoons continue to preserve this misperception. But, discoveries in recent decades, such as *Australopithecus afarensis*, show that even very early human ancestors stood upright, had feet and legs much like ours, but had brains relatively little larger than those of chimpanzees. Science, sooner or later, overcomes prejudices and misapprehensions that are due to cultural influences and personal bias. That is one of the powers of the scientific enterprise.



Hulking "cave man"

Upright *Australopithecus atarensis*

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