What is science?

Science is the concerted human effort to understand, or to understand better, the history of the natural world and how the natural world works, with observable physical evidence as the basis of that understanding[1]. It is done through observation of natural phenomena, and/or through experimentation that tries to simulate natural processes under controlled conditions. (There are, of course, more definitions of science.)

Consider some examples. An ecologist observing the territorial behaviors of bluebirds and a geologist examining the distribution of fossils in an outcrop are both scientists making observations in order to find patterns in natural phenomena. They just do it outdoors and thus entertain the general public with their behavior. An astrophysicist photographing distant galaxies and a climatologist sifting data from weather balloons similarly are also scientists making observations, but in more discrete settings.

The examples above are observational science, but there is also experimental science. A chemist observing the rates of one chemical reaction at a variety of temperatures and a nuclear physicist recording the results of bombardment of a particular kind of matter with neutrons are both scientists performing experiments to see what consistent patterns emerge. A biologist observing the reaction of a particular tissue to various stimulants is likewise experimenting to find patterns of behavior. These folks usually do their work in labs and wear impressive white lab coats, which seems to mean they make more money too.

The critical commonality is that all these people are making and recording observations of nature, or of simulations of nature, in order to learn more about how nature, in the broadest sense, works. We'll see below that one of their main goals is to show that old ideas (the ideas of scientists a century ago or perhaps just a year ago) are wrong and that, instead, new ideas may better explain nature.

So why do science? I - the individual perspective

So why are all these people described above doing what they're doing? In most cases, they're collecting information to test new ideas or to disprove old ones. Scientists become famous for discovering new things that change how we think about nature, whether the discovery is a new species of dinosaur or a new way in which atoms bond. Many scientists find their greatest joy in a previously unknown fact (a discovery) that explains something problem previously not explained, or that overturns some previously accepted idea.

That's the answer based on noble principles, and it probably explains why many people go into science as a career. On a pragmatic level, people also do science to earn their paychecks. Professors at most universities and many colleges are expected as part of their contractual obligations of employment to do research that makes new contributions to knowledge. If they don't, they lose their jobs, or at least they get lousy raises.

Scientists also work for corporations and are paid to generate new knowledge about how a particular chemical affects the growth of soybeans or how petroleum forms deep in the earth. These scientists get paid better, but they may work in obscurity because the knowledge they generate is kept secret by their employers for the development of new products or technologies. In fact, these folks at Megacorp do science, in that they and people within their company learn new things, but it may be years before their work becomes science in the sense of a contribution to humanity's body of knowledge beyond Megacorp's walls.

Why do Science? II - The Societal Perspective

If the ideas above help explain why individuals do science, one might still wonder why societies and nations pay those individuals to do science. Why does a society devote some of its resources to this business of developing new knowledge about the natural world, or what has motivated these scientists to devote their lives to developing this new knowledge?

One realm of answers lies in the desire to improve people's lives. Geneticists trying to understand how certain conditions are passed from generation to generation and biologists tracing the pathways by which diseases are transmitted are clearly seeking information that may better the lives of very ordinary people. Earth scientists developing better models for the prediction of weather or for the prediction of earthquakes, landslides, and volcanic eruptions are likewise seeking knowledge that can help avoid the hardships that have plagued humanity for centuries. Any society concerned about the welfare of its people, which is at the least any democratic society, will support efforts like these to better people's lives.

Another realm of answers lies in a society's desires for economic development. Many earth scientists devote their work to finding more efficient or more effective ways to discover or recover natural resources like petroleum and ores. Plant scientists seeking strains or species of fruiting plants for crops are ultimately working to increase the agricultural output that nutritionally and literally enriches nations. Chemists developing new chemical substances with potential technological applications and physicists developing new phenomena like superconductivity are likewise developing knowledge that may spur economic development. In a world where nations increasingly view themselves as caught up in economic competition, support of such science is nothing less than an investment in the economic future.

Another whole realm of answers lies in humanity's increasing control over our planet and its environment. Much science is done to understand how the toxins and wastes of our society pass through our water, soil, and air, potentially to our own detriment. Much science is also done to understand how changes that we cause in our atmosphere and oceans may change the climate in which we live and that controls our sources of food and water. In a sense, such science seeks to develop the owner's manual that human beings will need as they increasingly, if unwittingly, take control of the global ecosystem and a host of local ecosystems.

Lastly, societies support science because of simple curiosity and because of the satisfaction that comes from knowledge of the world around us. Few of us will ever derive any economic benefit from knowing that the starlight we see in a clear night sky left those stars thousands and even millions of years ago, so that we observe such light as messengers of a very distant past. However, the awe, perspective, and perhaps even serenity derived from that knowledge is very valuable to many of us. Likewise, few of us will derive greater physical well-being from watching a flowing stream and from reflecting on the hydrologic cycle through which that stream's water has passed, from the distant ocean to the floating clouds of our skies to the rains and storms upstream and now to the river channel at which we stand. However, the sense of interconnectedness that comes from such knowledge enriches our understanding of our world, and of our lives, in a very valuable way. By understanding the stars in our sky and the rivers under our bridges, we better understand who we are and our place in the world. When intangible benefits like these are combined with the more tangible ones outlined above, it's no wonder that most modern societies support scientific research for the improvement of our understanding of the world around us.

How Research becomes Scientific Knowledge

As our friends at Megacorp illustrate, doing research in the lab or in the field may be science, but it isn't necessarily a contribution to knowledge. No one in the scientific community will know about, or place much confidence in, a piece of scientific research until it is published in a peer-reviewed journal. They may hear about new research at a meeting or learn about it through the grapevine of newsgroups, but nothing's taken too seriously until publication of the data.

That means that our ecologist has to write a paper (called a "manuscript" for rather old-fashioned reasons). In the manuscript she justifies why her particular piece of research is significant, she details what methods she used in doing it, she reports exactly what she observed as the results, and then she explains what her observations mean relative to what was already known.

She then sends her manuscript to the editors of a scientific journal, who send it to two or three experts for review. If those experts report back that the research was done in a methodologically sound way and that the results contribute new and useful knowledge, the editor then approves publication, although almost inevitably with some changes or additions. Within a few months (we hope), the paper appears in a new issue of the journal, and scientists around the world learn about our ecologist's findings. They then decide for themselves whether they think the methods used were adequate and whether the results mean something new and exciting, and gradually the paper changes the way people think about the world.

Of course there are some subtleties in this business. If the manuscript was sent to a prestigious journal like *Science* or *Nature*, the competition for publication there means that the editors can select what they think are only the most ground-breaking manuscripts and reject the rest, even though the manuscripts are all well-done science. The authors of the rejected manuscripts then send their work to somewhat less exalted journals, where the manuscripts probably get published but are read by a somewhat smaller audience. At the other end of the spectrum may be the *South Georgia Journal of Backwater Studies,* where the editor gets relatively few submissions and can't be too picky about what he or she accepts into the journal, and not too many people read it. For better or worse, scientists are more likely to read, and more likely to accept, work published in widely-distributed major journals than in regional journals with small circulation.

To summarize, science becomes knowledge by publication of research results. It then may become more general knowledge as writers of textbooks pick and choose what to put in their texts, and as professors and teachers then decide what to stress from those textbooks. Publication is critical, although not all publication is created equal. The more a newly published piece of research challenges established ideas, the more it will be noted by other scientists and by the world in general.

Science and Change (and Miss Marple)

If scientists are constantly trying to make new discoveries or to develop new concepts and theories, then the body of knowledge produced by science should undergo constant change. Such change is progress toward a better understanding of nature. It is achieved by constantly questioning whether our current ideas are correct. As the famous American astronomer Maria Mitchell (1818-1889) put it, "Question everything".

The result is that theories come and go, or at least are modified through time, as old ideas are questioned and new evidence is discovered. In the words of Karl Popper, "Science is a history of corrected mistakes", and even Albert Einstein remarked of himself "That fellow Einstein . . . every year retracts what he wrote the year before". Many scientists have remarked that they would like to return to life in a few centuries to see what new knowledge and new ideas have been developed by then - and to see which of their own century's ideas have been discarded. Our ideas today should be compatible with all the evidence we have, and we hope that our ideas will survive the tests of the future. However, any look at history forces us to realize that the future is likely to provide new evidence that will lead to at least somewhat different interpretations.

Some scientists become sufficiently ego-involved that they refuse to accept new evidence and new ideas. In that case, in the words of one pundit, "science advances funeral by funeral". However, most scientists realize that today's theories are probably the future's outmoded ideas, and the best we can hope is that our theories will survive with some tinkering and fine-tuning by future generations.

We can go back to Copernicus to illustrate this. Most of us today, if asked on a street corner, would say that we accept Copernicus's idea that the earth moves around the sun - we would say that the heliocentric theory seems correct. However, Copernicus himself maintained that the orbits of the planets around the sun were perfectly circular. A couple of centuries later, in Newton's time, it became apparent that those orbits are ellipses. The heliocentric theory wasn't discarded; it was just modified to account for more detailed new observations. In the twentieth century, we've additionally found that the exact shapes of the ellipses aren't constant (hence the Milankovitch cycles that may have influenced the periodicity of glaciation). However, we haven't gone back to the idea of an earth-centered universe. Instead, we still accept a heliocentric theory - it's just one that's been modified through time as new data have emerged.

The notion that scientific ideas change, and should be expected to change, is sometimes lost on the more vociferous critics of science. One good example is the Big Bang theory. Every new astronomical discovery seems to prompt someone to say "See, the Big Bang theory didn't predict that, so the whole thing must be wrong". Instead, the discovery prompts a change, usually a minor one, in the theory. However, once the astrophysicists have tinkered with the theory's details enough to account for the new discovery, the critics then say "See, the Big Bang theory has been discarded". Instead, it's just been modified to account for new data, which is exactly what we've said ought to happen through time to any scientific idea.

Try an analogy: Imagine that your favorite fictional detective (Sherlock Holmes, Miss Marple, Nancy Drew, or whoever) is working on a difficult case in which the clues only come by fits and starts. Most detectives keep their working hypotheses to themselves until they've solved the case. However, let's assume that our detective decides this time to think out loud as the story unfolds, revealing their current prime suspect and hypothesized chronology of the crime as they go along. Now introduce a character who accompanies the detective and who, as each clue is uncovered, exclaims, "See, this changes what you thought before - you must be all wrong about everything!" Our detective will think, but probably have the grace to not say, "No, the new evidence just helps me sharpen the cloudy picture I had before". The same is true in science, except that nature never breaks down in the last scene and explains how she done it.

Science and Knowledge

So what does all this mean? It means that science does not presently, and probably never can, give statements of absolute eternal truth - it only provides theories. We know that those theories will probably be refined in the future, and some of them may even be discarded in favor of theories that make more sense in light of data generated by future scientists. However, our present theories are our best available explanations of the world. They explain, and have been tested against, a vast amount of information.

Consider some of the information against which we've tested our theories:

- We've examined the DNA, cells, tissues, organs, and bodies of thousands if not millions of species of organisms, from bacteria to cacti to great blue whales, at scales from electron microscopy to global ecology.

- We've examined the physical behavior of particles ranging in size from quarks to stars and at times scales from femtoseconds to millions of years.
- We've characterized the 90 or so chemical elements that occur naturally on earth and several more that we've synthesized.
- We've poked at nearly every rock on the earth's surface and drilled as much as six miles into the earth to recover and examine more.
- We've used seismology to study the earth's internal structure, both detecting shallow faults and examining the behavior of the planet's core.
- We've studied the earth's oceans with dredges, bottles, buoys, boats, drillships, submersibles, and satellites.
- We've monitored and sampled Earth's atmosphere at a global scale on a minute-by-minute basis.
- We've scanned outer space with telescopes employing radiation ranging in wavelength from infrared to X-rays, and we've sent probes to examine both our sun and the distant planets of our solar system.
- We've personally explored the surface of our moon and brought back rocks from there, and we've sampled a huge number of meteorites to learn more about matter from beyond our planet.

We will do more in the centuries to come, but we've already assembled a vast array of information on which to build the theories that are our present scientific understanding of the universe.

This leaves people with a choice today. One option is to accept, perhaps with some skepticism, the scientific (and only theoretical) understanding of the natural world, which is derived from all the observations and measurements described above. The other option, or perhaps an other option, is to accept traditional understandings[3] of the natural world developed centuries or even millenia ago by people who, regardless how wise or well-meaning, had only sharp eyes and fertile imaginations as their best tools.

What Science Isn't, Part I: A Historical Perspective

Many historians suggest that modern science began around 1600 in the time and with the efforts of Galileo Galilei (1564-1642), Johannes Kepler (1571-1630), and Francis Bacon (1561-1626). Their era punctuated the change from scholasticism of the Middle Ages and Renaissance to science, as we know it. **Scholasticism** largely involved deductive reasoning from principles supplied by Aristotle, by scripture, or by notions of perfection (which largely involved circles and spheres). It was thus a "top-down" intellectual enterprise. **Modern science** instead involved induction from multiple observations of nature, and so worked "bottom-up" from basic observation or experiment to generalization. In the words of Bacon's *Novum organum*, "For man is but the servant or interpreter of nature; what he does and what he knows is only what he has observed of nature's order in fact or in thought; beyond this he knows nothing and can do nothing. . . . All depends on keeping the eye steadily fixed upon the facts of nature and so receiving the images simply as they are."

Galileo's and Kepler's work exemplified this fundamental change in attitude. Medieval thinking had assumed a centrality of humanity, so that the earth on which humans lived was thought to be the center of the universe. It had also assumed a perfection requiring orbits of heavenly bodies to be circular. Nicolaus Copernicus (1473-1543, and thus a hundred years before Galileo and Kepler) had cautiously broken with the first of these assumptions to conclude tentatively that the earth orbited the sun, but he clung to the idea of a perfectly circular orbit. Galileo argued much more forcefully for an earth orbiting the sun, ultimately breaking the earth-centered view that was based on human-centered logic. Kepler showed that the orbits of the planets are ellipses, rather than the circles required of a philosophically perfect universe. More recent observations - that those orbits are changing ellipses, that the earth is not perfectly spherical but is an oblate spheroid, and that the sun occupies no central position in just one galaxy among billions of galaxies - would all be very distasteful to the scholastic view of the world, which assumed geometric perfection and human or earthly centrality.

To summarize: The logic of modern science requires that observations or facts govern the validity of generalizations or theories. Previous thinking had often gone the opposite direction. Galileo was reminded of that previous direction when he was taken to Rome and condemned because of his "proposition that the sun is in the center of the world and immovable from its place is absurd . . . because it is expressly contrary to Holy Scripture" (to quote the official judgment of the court). The success and everyday application of modern physics, chemistry, biology, geology, and the other sciences is forceful evidence of the validity of the modern approach.

What Science Isn't, Part II: Science Isn't Art

To say science isn't art may seem trivial, but comparing the two helps illustrate what science is. We'll start with art, and then move to science.

Art is the attempt to express an individual's feelings or ideas about something in a way that others find beautiful, graceful, or at least aesthetically satisfying. Thus art is very individualistic. Outside the performing arts, art is almost always produced by individuals, because it has to have purity of expression that can only come from one person. In the performing arts, art is generally the concept of one person (a composer or choreographer), although it is executed by many. Art is also individualistic in that a painting or sculpture left in the studio is nonetheless art, even if no one else sees it, and even if anyone who saw it thought it ugly, graceless, or tasteless. Un-displayed or unloved art is still art in that it expresses the concept of the artist.

The second part of our definition suggests that art ought to be beautiful or aesthetically satisfying. Until the twentieth century, beauty was a requirement of art. In the twentieth century expression became so important, or the expressed concepts were often so distressing, that pure beauty may have suffered at times. Aesthetics nonetheless remain critical to art. Certainly in the art most popular today (Impressionist paintings; the music of Bach, Mozart, and Beethoven, and even much rock music; ballet and modern dance; poetry from Shakespeare to haikus), beauty remains a critical component.

Science, in contrast, is the attempt to reach demonstrable, replicable, conclusions about the natural world (and social science is the corresponding attempt to reach demonstrable conclusions about the social or human world). Individualism exists, in that what each scientist studies and how they study it are somewhat open to their choice. However, the conclusions reached have to be demonstrable to others with physical evidence. If an artist says, "This work expresses something deep in my heart", everyone nods approvingly. If a scientist says, "I don't have any evidence to show you, but deep in my heart I know . . .", everyone rolls their eyes and leaves the room as quickly as possible. The non-individualistic nature of science is also reflected by how much scientific research is done by groups: a single-authored paper in particle physics is about as common as a multi-authored novel.

Secondly, in working from our definition of art but now comparing science to it, science doesn't have to be beautiful or aesthetically satisfying, or even emotionally satisfying. Electron orbitals can be shown to distorted, crystal structures can be shown to have defects, ocean basins and their currents can be shown to be asymmetric, planets can be shown to be non-spherical, and that's OK - even though a geometrically perfect world might be more beautiful. Atoms can be shown to decay, species can be shown to change, continents can be shown to move, merge, and split in random ways, the universe can be shown to be changing explosively, and that's OK - even though an invariant timeless world might be more aesthetically satisfying. Humans can be shown to be ill-designed animals genealogically descended from scruffy or slimy ancestors, and that's OK - even though it's not emotionally satisfying to humans.

To summarize (and generalize): art is largely an individual's effort to communicate his or her ideas or feelings in a beautiful way. Science is a group effort to characterize reality. Aesthetics, although nice if available, don't count for much in science.

What Science Isn't, Part III: Science is not Technology

One of the mistakes many people make in thinking about science is to confuse it with technology. As a result, science often either receives undue credit (for the "miracles of modern science" in one's kitchen) or undue blame (for everything from overly firm tomatoes to nuclear war). In fact, science doesn't make things. Scientists developed the understanding of radiation sufficient for the invention of the microwave oven, but neither making a microwave oven nor using it are science. Scientists are in the business of generating knowledge, whereas engineers are in the business of generating technology.

People doing science often use sophisticated technology, but science doesn't require it. Our ecologist observing natural bird behavior and our geologist examining an outcrop neither use particularly sophisticated technology. In fact, the only technology in common to all science is the notebook in which observations are recorded.

In short, science often leads to technology, and it often uses technology, but it isn't technology, and in fact it can operate quite independently of technology.

What Science Isn't, Part IV: Science isn't Truth and it isn't certainty

Some people assume that scientists have generated a body of knowledge that is sure to be true. Some ideas, after all, are known with enough certainty that most of us take them for granted. An example is our common assumption that the earth orbits the sun. Much scientific evidence supports that idea, which is the heliocentric theory of the solar system, and most of us take it as "true". However, no human has observed the solar system and seen the earth traveling in an orbit around the sun. It's just a theory, if a nearly inescapable one.

In that sense, most scientists will concede that, although they seek Truth, they don't know or generate Truth. They propose and test theories, knowing that future evidence may cause refinement, revision, or even rejection of today's theories. Ask a scientist about an issue that's not directly observable, and you probably hear an answer that starts with something like "The evidence suggests that . . ." or "Our current understanding is . . .". You're not hearing waffling or indecision. You're hearing a reasoned recognition that we can't know many things with absolute certainty - we only know the observable evidence. However, we can reach the best possible conclusion based on the most complete and modern evidence available.

That contrasts strongly with the knowledge claimed by many other people. Many people claim that they, or a book or books they endorse, hold all relevant knowledge and that such knowledge is absolutely and unquestionably true. The Bible, as an example, is often held up as containing all knowledge, and as being literal and infallible Truth. No science book has ever been endorsed that way, nor should it ever be.

As an example, consider the question "How did the world begin?" A scientist's answer will begin with the evidence that we've gleaned from decades if not centuries of astronomical study, which includes several lines of evidence about the motions of galaxies. It will conclude with a theory that fits the accumulated evidence. There won't be, or at least ought not be, any statement about absolute truth.

In contrast, some other people will answer that the world was created by a certain deity a certain number of years ago. If asked about their level of certainty, these people generally respond that they have absolutely no uncertainty. No scientist thinking about what he or she is saying will answer with that degree of certainty, regardless of the evidence available to him or her, nor will they lay that kind of claim to Truth. They may have a high level of confidence if there's abundant evidence, but they won't claim absolute Truth or absolute certainty.

It's worth remembering that a person's admission of uncertainty doesn't mean they're wrong, whether the issue is in politics, economics, religion, or science. In fact, a person who admits some uncertainty in their thinking is often closer to the truth, or at least understands the issues better, than someone who claims absolute certainty. Shouting loudest does not generate truth.

Summary

Science is the concerted effort by very real human beings to understand the history of the natural world and how the natural world works. Observable physical evidence, either from observations of nature or from experiments that try to simulate nature, is the basis of that understanding. The results of, and inferences from, those observations and experiments become scientific knowledge only after publication. The point of publication is to change previous ideas. Thus theories, the large-scale concepts that are based on huge amounts of data and try to explain and predict large bodies of phenomena, may be powerful ideas, but they are constantly subject to revision or even rejection as new knowledge emerges. The result is that scientific knowledge is constantly changing but hopefully proceeding toward a more accurate view of the world.