Misinterpretations of the scientific process

MISCONCEPTION: Science is a collection of facts.

CORRECTION: Because science classes sometimes revolve around dense textbooks, it's easy to think that's all there is to science: facts in a textbook. But that's only part of the picture. Science *is* a body of knowledge that one can learn about in textbooks, but it is also a process. Science is an exciting and dynamic process for discovering how the world works and building that knowledge into powerful and coherent frameworks.

MISCONCEPTION: Science is complete.

CORRECTION: Since much of what is taught in introductory science courses is knowledge that was constructed in the 19th and 20th centuries, it's easy to think that science is finished — that we've already discovered most of what there is to know about the natural world. This is far from accurate. Science is an ongoing process, and there is much more yet to learn about the world. In fact, in science, making a key discovery often leads to many new questions ripe for investigation. Furthermore, scientists are constantly elaborating, refining, and revising established scientific ideas based on new evidence and perspectives.

MISCONCEPTION: There is a single Scientific Method that all scientists follow.

CORRECTION: "The Scientific Method" is often taught in science courses as a simple way to understand the basics of scientific testing. In fact, the Scientific Method represents how scientists usually write up the results of their studies (and how a few investigations are actually done), but it is a grossly oversimplified representation of how scientists generally build knowledge. The process of science is exciting, complex, and unpredictable. It involves many different people, engaged in many different activities, in many different orders.

MISCONCEPTION: The process of science is purely analytic and does not involve creativity.

CORRECTION: Perhaps because the Scientific Method presents a linear and rigid representation of the process of science, many people think that doing science involves closely following a series of steps, with no room for creativity and inspiration. In fact, many scientists recognize that creative thinking is one of the most important skills they have — whether that creativity is used to come up with an alternative hypothesis, to devise a new way of testing an idea, or to look at old data in a new light. Creativity is critical to science!

MISCONCEPTION: When scientists analyze a problem, they must use either inductive or deductive reasoning.

CORRECTION: Scientists use all sorts of different reasoning modes at different times — and sometimes at the same time — when analyzing a problem. They also use their creativity to come up with new ideas, explanations, and tests. This isn't an either/or choice between induction and deduction. Scientific analysis often involves jumping back and forth among different modes of reasoning and creative brainstorming! What's important about scientific reasoning is not what all the different modes of reasoning are called, but the fact that the process relies on careful, logical consideration of how evidence supports or does not support an idea, of how different scientific ideas are related to one another, and of what sorts of things we can expect to observe if a particular idea is true.

MISCONCEPTION: Experiments are a necessary part of the scientific process. Without an experiment, a study is not rigorous or scientific.

CORRECTION: Perhaps because the Scientific Method and popular portrayals of science emphasize experiments, many people think that science can't be done *without* an experiment. In fact, there are *many* ways to test almost any scientific idea; experimentation is only one approach. Some ideas are best tested by setting up a controlled experiment in a lab, some by making detailed observations of the natural world, and some with a combination of strategies.

MISCONCEPTION: "Hard" sciences are more rigorous and scientific than "soft" sciences.

CORRECTION: Some scientists and philosophers have tried to draw a line between "hard" sciences (e.g., chemistry and physics) and "soft" ones (e.g., psychology and sociology). The thinking was that hard science used more rigorous, quantitative methods than soft science did and so were more trustworthy. In fact, the rigor of a scientific study has much more to do with the investigator's approach than with the discipline. Many psychology studies, for example, are carefully controlled, rely on large sample sizes, and are highly quantitative.

MISCONCEPTION: Scientific ideas are absolute and unchanging.

CORRECTION: Because science textbooks change very little from year to year, it's easy to imagine that scientific ideas don't change at all. It's true that some scientific ideas are so well established and supported by so many lines of evidence, they are unlikely to be completely overturned. However, even these established ideas are subject to modification based on new evidence and perspectives. Furthermore, at the cutting edge of scientific research — areas of knowledge that are difficult to represent in introductory textbooks — scientific ideas may change rapidly as scientists test out many different possible explanations trying to figure out which are the most accurate.

MISCONCEPTION: Because scientific ideas are tentative and subject to change, they can't be trusted.

CORRECTION: Especially when it comes to scientific findings about health and medicine, it can sometimes seem as though scientists are always changing their minds. One month the newspaper warns you away from chocolate's saturated fat and sugar; the next month, chocolate companies are bragging about chocolate's antioxidants and lack of trans-fats. There are several reasons for such apparent reversals. First, press coverage tends to draw particular attention to disagreements or ideas that conflict with past views. Second, ideas at the cutting edge of research (e.g., regarding new medical studies) may change rapidly as scientists test out many different possible explanations trying to figure out which are the most accurate. This is a normal and healthy part of the process of science. While it's true that all scientific ideas are subject to change if warranted by the evidence, many scientific ideas (e.g., evolutionary theory, foundational ideas in chemistry) are supported by many lines of evidence, are extremely reliable, and are unlikely to change.

MISCONCEPTION: Scientists' observations directly tell them how things work (i.e., knowledge is "read off" nature, not built).

CORRECTION: Because science relies on observation and because the process of science is unfamiliar to many, it may seem as though scientists build knowledge directly through observation. Observation *is* critical in science, but scientists often make inferences about what those observations mean. Observations are part of a complex process that involves coming up with ideas about how the natural world works and seeing if observations back those explanations up. Learning about the inner workings of the natural world is less like reading a book and more like writing a non-fiction book — trying out different ideas, rephrasing, running drafts by other people, and modifying text in order to present the clearest and most accurate explanations for what we observe in the natural world.

MISCONCEPTION: Science proves ideas.

CORRECTION: Journalists often write about "scientific proof" and some scientists talk about it, but in fact, the concept of proof — real, absolute proof — is not particularly scientific. Science is based on the principle that *any* idea, no matter how widely accepted today, could be overturned tomorrow if the evidence warranted it. Science accepts or rejects ideas based on the evidence; it does not prove or disprove them.

MISCONCEPTION: Science can only disprove ideas.

CORRECTION: This misconception is based on the idea of falsification, philosopher Karl Popper's influential account of scientific justification, which suggests that all science can do is reject, or falsify, hypotheses — that science cannot find evidence that *supports* one idea over others. Falsification was a popular philosophical doctrine — especially with scientists — but it was soon recognized that falsification wasn't a very complete or accurate picture of how scientific knowledge is built. In science, ideas can never be completely proved or completely disproved. Instead, science accepts or rejects ideas based on supporting and refuting evidence, and may revise those conclusions if warranted by new evidence or perspectives.

MISCONCEPTION: If evidence supports a hypothesis, it is upgraded to a theory. If the theory then garners even more support, it may be upgraded to a law.

CORRECTION: This misconception may be reinforced by introductory science courses that treat hypotheses as "things we're not sure about yet" and that only explore established and accepted theories. In fact, hypotheses, theories, and laws are rather like apples, oranges, and kumquats: one cannot grow into another, no matter how much fertilizer and water are offered. Hypotheses, theories, and laws are all scientific explanations that differ in breadth — not in level of support. Hypotheses are explanations that are limited in scope, applying to fairly narrow range of phenomena. The term *law* is sometimes used to refer to an idea about how observable phenomena are related — but the term is also used in other ways within science. Theories are deep explanations that apply to a broad range of phenomena and that may integrate many hypotheses and laws.

MISCONCEPTION: Scientific ideas are judged democratically based on popularity.

CORRECTION: When newspapers make statements like, "most scientists agree that human activity is the culprit behind global warming," it's easy to imagine that scientists hold an annual caucus and vote for their favorite hypotheses. But of course, that's not quite how it works. Scientific ideas are judged not by their popularity, but on the basis of the evidence supporting or contradicting them. A hypothesis or theory comes to be accepted by many scientists (usually over the course of several years — or decades!) once it has garnered many lines of supporting evidence and has stood up to the scrutiny of the scientific community. A hypothesis accepted by "most scientists," may not be "liked" or have positive repercussions, but it is one that science has judged likely to be accurate based on the evidence.

MISCONCEPTION: The job of a scientist is to find support for his or her hypotheses.

CORRECTION: This misconception likely stems from introductory science labs, with their emphasis on getting the "right" answer and with congratulations handed out for having the "correct" hypothesis all along. In fact, science gains as much from figuring out which hypotheses are likely to be wrong as it does from figuring out which are supported by the evidence. Scientists may have personal favorite hypotheses, but they strive to consider multiple hypotheses and be unbiased when evaluating them against the evidence. A scientist who finds evidence contradicting a favorite hypothesis may be surprised and probably disappointed, but can rest easy knowing that he or she has made a valuable contribution to science.

MISCONCEPTION: Scientists are judged on the basis of how many correct hypotheses they propose (i.e., good scientists are the ones who are "right" most often).

CORRECTION: The scientific community *does* value individuals who have good intuition and think up creative explanations that turn out to be correct — but it *also* values scientists who are able to think up creative ways to test a new idea (even if the test ends up contradicting the idea) and who spot the fatal flaw in a particular argument or test. In science, gathering evidence to determine the accuracy of an explanation is just as important as coming up with the explanation that winds up being supported by the evidence.

MISCONCEPTION: Investigations that don't reach a firm conclusion are useless and unpublishable.

CORRECTION: Perhaps because the last step of the Scientific Method is usually "draw a conclusion," it's easy to imagine that studies that don't reach a clear conclusion must not be scientific or important. In fact, *most* scientific studies don't reach "firm" conclusions. Scientific articles usually end with a discussion of the limitations of the tests performed and the alternative hypotheses that might account for the phenomenon. That's the nature of scientific knowledge — it's inherently tentative and could be overturned if new evidence, new interpretations, or a better explanation come along. In science, studies that carefully analyze the strengths and weaknesses of the test performed and of the different alternative explanations are particularly valuable since they encourage others to more thoroughly scrutinize the ideas and evidence and to develop new ways to test the ideas.

MISCONCEPTION: Scientists are completely objective in their evaluation of scientific ideas and evidence.

CORRECTION: Scientists do strive to be unbiased as they consider different scientific ideas, but scientists are people too. They have different personal beliefs and goals — and may favor different hypotheses for different reasons. Individual scientists may not be completely objective, but science can overcome this hurdle through the action of the scientific community, which scrutinizes scientific work and helps balance biases.

MISCONCEPTION: Science is pure. Scientists work without considering the applications of their ideas.

CORRECTION: It's true that some scientific research is performed without any attention to its applications, but this is certainly not true of all science. Many scientists choose specific areas of research (e.g., malaria genetics) because of the practical ramifications new knowledge in these areas might have. And often, basic research that is performed without any aim toward potential applications later winds up being extremely useful.

Misunderstandings of the limits of science

MISCONCEPTION: Science contradicts the existence of God.

CORRECTION: Because of some vocal individuals (both inside and outside of science) stridently declaring their beliefs, it's easy to get the impression that science and religion are at war. In fact, people of many different faiths and levels of scientific expertise see no contradiction at all between science and religion. Because science deals only with natural phenomena and explanations, it cannot support or contradict the existence of supernatural entities — like God.

MISCONCEPTION: Science and technology can solve all our problems.

CORRECTION: The feats accomplished through the application of scientific knowledge are truly astounding. Science has helped us eradicate deadly diseases, communicate with people all over the world, and build technologies that make our lives easier everyday. But for all scientific innovations, the costs must be carefully weighed against the benefits. And, of course, there's no guarantee that solutions for some problems (e.g., finding an HIV vaccine) exist — though science is likely to help us discover them if they do exist. Furthermore, some important human concerns (e.g. some spiritual and aesthetic questions) cannot be addressed by science at all. Science is a marvelous tool for helping us understand the natural world, but it is not a cure-all for whatever problems we encounter.

Misleading stereotypes of scientists

MISCONCEPTION: Science is a solitary pursuit.

CORRECTION: When scientists are portrayed in movies and television shows, they are often ensconced in silent laboratories, alone with their bubbling test-tubes. This can make science seem isolating. In fact, many scientists work in busy labs or field stations, surrounded by other scientists and students. Scientists often collaborate on studies with one another, mentor less experienced scientists, and just chat about their work over coffee. Even the rare scientist who works entirely alone depends on interactions with the rest of the scientific community to scrutinize his or her work and get ideas for new studies. Science is a social endeavor.

MISCONCEPTION: Science is done by "old, white men."

CORRECTION: While it is true that Western science used to be the domain of white males, this is no longer the case. The diversity of the scientific community is expanding rapidly. Science is open to anyone who is curious about the natural world and who wants to take a scientific approach to his or her investigations.

MISCONCEPTION: Scientists are atheists.

CORRECTION: This is far from true. A 2005 survey of scientists at top research universities found that more than 48% had a religious affiliation and that more than 75% believed that religions convey important truths.[1] Some scientists are not religious, but many others subscribe to a specific faith and/or believe in higher powers. Science itself is a secular pursuit, but welcomes participants from all religious faiths.

Vocabulary mix-ups

Some misconceptions occur simply because scientific language and everyday language use some of the same words differently.

- **Fact**: Facts are statements that we know to be true through direct observation. In everyday usage, facts are a highly valued form of knowledge because we can be so confident in them. Scientific thinking, however, recognizes that, though facts are important, we can only be completely confident about relatively simple statements. For example, it may be a fact that there are three trees in your backyard. However, our knowledge of how all trees are related to one another is not a fact; it is a complex body of knowledge based on many different lines of evidence and reasoning that may change as new evidence is discovered and as old evidence is interpreted in new ways. Though our knowledge of tree relationships is not a fact, it is broadly applicable, useful in many situations, and synthesizes many individual facts into a broader framework. Science values facts but recognizes that many forms of knowledge are more powerful than simple facts.

- **Law**: In everyday language, a law is a rule that must be abided or something that can be relied upon to occur in a particular situation. Scientific laws, on the other hand, are less rigid. They may have exceptions, and, like other scientific knowledge, may be modified or rejected based on new evidence and perspectives. In science, the term *law* usually refers to a generalization about data and is a compact way of describing what we'd expect to happen in a particular situation. Some laws are non-mechanistic statements about the relationship among observable phenomena. For example, the ideal gas law describes how the pressure, volume, and temperature of a particular amount of gas are related to one another. It does not describe how gases *must* behave; we know that gases do not precisely conform to the ideal gas law. Other laws deal with phenomena that are not directly observable. For example, the second law of thermodynamics deals with entropy, which is not directly observable in the same way that volume and pressure are. Still other laws offer more mechanistic explanations of phenomena. For example, Mendel's first law offers a model of how genes are distributed to gametes and offspring that helps us make predictions about the outcomes of genetic crosses. The term *law* may be used to describe many different forms of scientific knowledge, and whether or not a particular idea is called a law has much to do with its discipline and the time period in which it was first developed.

- **Observation**: In everyday language, the word *observation* generally means something that we've seen with our own eyes. In science, the term is used more broadly. Scientific observations can be made directly with our own senses or may be made indirectly through the use of tools like thermometers, pH test kits, Geiger counters, etc. We can't actually *see* beta particles, but we can observe them using a Geiger counter.

- **Hypothesis**: In everyday language, the word *hypothesis* usually refers to an educated guess — or an idea that we are quite uncertain about. Scientific hypotheses, however, are much more informed than any guess and are usually based on prior experience, scientific background knowledge, preliminary observations, and logic. In addition, hypotheses are often supported by many different lines of evidence — in which case, scientists are more confident in them than they would be in any mere "guess." To further complicate matters, science textbooks frequently misuse the term in a slightly different way. They may ask students to make a *hypothesis* about the outcome of an experiment (e.g., table salt will dissolve in water more quickly than rock salt will). This is simply a prediction or a guess (even if a well-informed one) about the outcome of an experiment. Scientific hypotheses, on the other hand, have explanatory power — they are explanations for phenomena. The idea that table salt dissolves faster than rock salt is not very hypothesis-like because it is not very explanatory. A more scientific (i.e., more explanatory) hypothesis might be "The amount of surface area a substance has affects how quickly it can dissolve. More surface area means a faster rate of dissolution." This hypothesis has some explanatory power — it gives us an idea of *why* a particular phenomenon occurs — and it is testable because it generates expectations about what we should observe in different situations. If the hypothesis is accurate, then we'd expect that, for example, sugar processed to a powder should dissolve more quickly than granular sugar. Students could examine rates of dissolution of many different substances in powdered, granular, and pellet form to further test the idea. The statement "Table salt will dissolve in water more quickly than rock salt" is not a hypothesis, but an expectation generated by a hypothesis. Textbooks and science labs can lead to confusions about the difference between a hypothesis and an expectation regarding the outcome of a scientific test.

- **Theory**: In everyday language, the word *theory* is often used to mean a hunch with little evidential support. Scientific 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, and can be used to make predictions about many different sorts of situations. A theory is most acceptable to the scientific community when it is strongly supported by many different lines of evidence — but even theories may be modified or overturned if warranted by new evidence and perspectives.

- **Falsifiable**: The word *falsifiable* isn't used much in everyday language, but when it is, it is often applied to ideas that have been shown to be untrue. When that's the case — when an idea has been shown to be false — a scientist would say that it has been falsified. A falsifi*able* idea, on the other hand, is one for which there is a conceivable test that might produce evidence proving the idea false. Scientists and others influenced by the ideas of the philosopher Karl Popper sometimes assert that only falsifiable ideas are scientific. However, we now recognize that science cannot once-and-for-all prove any idea to be false (or true for that matter). Furthermore, it's clear that evidence can play a role in supporting particular ideas over others — not just in ruling some ideas out, as implied by the falsifiability criterion. When a scientist says *falsifiable*, he or she probably actually means something like *testable*, the term we use in this website to avoid confusion. A testable idea is one about which we could gather evidence to help determine whether or not the idea is accurate.

- **Uncertainty**: In everyday language, uncertainty suggests the state of being unsure of something. Scientists, however, usually use the word when referring to measurements. The uncertainty of a measurement (not to be confused with the inherent provisionality of all scientific ideas!) is the range of values within which the true value is likely to fall. In science, uncertainty is not a bad thing; it's simply a fact of life. Every measurement has some uncertainty. If you measure the length of a pen with a standard ruler, you won't be able to tell whether its length is 5.880 inches, 5.875 inches, or 5.870 inches. A ruler with more precision will help narrow that range, but cannot eliminate uncertainty entirely.

- **Error**: In everyday language, an error is simply a mistake, but in science, error has a precise statistical meaning. An error is the difference between a measurement and the true value, often resulting from taking a sample. For example, imagine that you want to know if corn plants produce more massive ears when grown with a new fertilizer, and so you weigh ears of corn from those plants. You take the mass of your sample of 50 ears of corn and calculate an average. That average is a good estimate of what you are really interested in: the average mass of *all* ears of corn that could be grown with this fertilizer. Your estimate is not a mistake — but it does have an error (in the statistical sense of the word) since your estimate is not the true value. Sampling error of the sort described above is inherent whenever a smaller sample is taken to represent a larger entity. Another sort of error results from systematic biases in measurement (e.g., if your scale were calibrated improperly, all of your measurements would be off). Systematic error biases measurements in a particular direction and can be more difficult to quantify than sampling error.

- **Prediction**: In everyday language, *prediction* generally refers to something that a fortune teller makes about the future. In science, the term *prediction* generally means "what we would expect to happen or what we would expect to observe if this idea were accurate." Sometimes, these scientific predictions have nothing at all to do with the future. For example, scientists have hypothesized that a huge asteroid struck the Earth 4.5 billion years ago, flinging off debris that formed the moon. If this idea were true, we would *predict* that the moon today would have a similar composition to that of the Earth's crust 4.5 billion years ago — a prediction which does seem to be accurate. This hypothesis deals with the deep history of our solar system and yet it involves predictions — in the scientific sense of the word. Ironically, scientific predictions often have to do with past events. In this website, we've tried to reduce confusion by using the words *expect* and *expectation* instead of *predict* and *prediction*.

- **Belief/believe**: When we, in everyday language, say that we believe in something, we may mean many things — that we support a cause, that we have faith in an idea, or that we think something is accurate. The word *belief* is often associated with ideas about which we have strong convictions, regardless of the evidence for or against them. This can generate confusion when a scientist claims to "believe in" a scientific hypothesis or theory. In fact, the scientist probably means that he or she "accepts" the idea — in other words, that he or she thinks the scientific idea is the most accurate available based on a critical evaluation of the evidence. Scientific ideas should always be accepted or rejected based on the evidence for or against them — not based on faith, dogma, or personal conviction.