Science as Storytelling

Barry R. Bickmore and David A. Grandy

Much of our modern culture revolves around something called "science." Governments want "scientific" analysis of various problems to guide policymaking. News reports detail the latest "scientific" studies about human health. People worry about whether their religion conflicts with "science." But what is science? This turns out to be a complicated and controversial question, and whenever we try to come up with a really precise definition, we end up calling some activities "science" that we would rather exclude, or excluding some activities we would like to include.[1] For example, some people distinguish science from other activities by noting that scientists perform experiments. However, some sciences aren't particularly experimental—for example, it is hard to imagine astronomers performing experiments on stars that are millions of light-years away. On the other hand, astronomers do collect and record observations, even if these cannot properly be called "experiments." Is the collection of observations of the natural world the defining feature of science? Apparently it isn't, since astrologers have been observing and recording the motions of heavenly bodies for millennia, and most people would not classify astrology as science. Scientists typically go on to explain their observations by creating theories that might be used to predict or control future events. However, astrologers also explain their observations by creating theories, and they certainly try

1. Larry Laudan, "The Demise of the Demarcation Problem," in *But Is It Science? The Philosophical Question in the Creation/Evolution Controversy,* ed. Michael Ruse (Amherst, N.Y.: Prometheus Books, 1996), 337–50.

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We originally wrote a version of this essay for use in introductory college science courses to address a number of prevalent issues with teaching the nature of science and how it relates to religion. Students commonly develop a simplistic view of science as "just the facts," which can lead to a tendency to dismiss scientific conclusions that challenge their preconceived notions—especially those connected with religious or political views.[1] Because all scientific reasoning includes components that go beyond "the facts," it is never difficult for those with naïve views of the nature of science to find reasons to dismiss a theory that makes them uncomfortable. Similarly, many scientists are not religious, and those who are tend to gravitate toward religious views that downplay the supernatural.[2] In fact, some scientists share in certain inaccurate views of the nature of science.[3]

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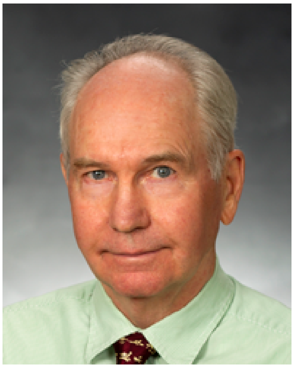
1. D. M. Moss, E. D. Abrams, and J. Robb, "Examining Student Conceptions of the Nature of Science," *International Journal of Science Education* 23, no. 8 (2001): 771–90; J. L. Rudolph and J. Stewart, "Evolution and the Nature of Science: On the Historical Discord and Its Implications for Education," *Journal of Research in Science Teaching* 35, no. 10 (1998): 1069–89; M. F. Antolin and J. M. Herbers, "Perspective: Evolution's Struggle for Existence in America's Public Schools," *Evolution* 55, no. 12 (2001): 2379–88; P. Farber, "Teaching Evolution and the Nature of Science," *American Biology Teacher* 65, no. 5 (2003): 347–54; R. G. Sprackland, "Teaching about Origins: A Scientist Explains Why Intelligent Design Isn't Science," *American School Board Journal* 192, no. 11 (2005): 26–30.

2. E. H. Ecklund and C. P. Sheitle, "Religion among Academic Scientists: Distinctions, Disciplines, and Demographics," *Social Problems* 54, no. 2 (2007): 289–307.

3. J. C. Pitt, "The Myth of Science Education," *Studies in Philosophy and Education* 10, no. 1 (1990): 7–17; F. Abd-El-Khalick and N. G. Lederman, "Improving Science Teachers' Conceptions of Nature of Science:

The result is that most science professors would rather avoid talking about the science-religion interface, but their students almost inevitably bring it up.[4] Common responses by the professors can be perceived as dismissive of some students' religious views. The "science as storytelling" approach is designed to help science students (and professors) gain a more productive view of both the nature of science and the science-religion interface. This approach has been shown to be effective for these purposes in multiple science courses, and at both secular and religious colleges.[5]



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A Critical Review of the Literature," *International Journal of Science Education* 22, no. 7 (2000): 665–701.

4. Ecklund and Sheitle, "Religion among Academic Scientists," 289–307.

5. Barry R. Bickmore, Kirsten R. Thompson, David A. Grandy, and Teagan Tomlin, "Commentary: On Teaching the Nature of Science and the Science-Religion Interface," *Journal of Geoscience Education* 58, no. 3 (2009): 168–77; Barry R. Bickmore, Kirsten R. Thompson, David A. Grandy, and Teagan Tomlin, "Science as Storytelling for Teaching the Nature of Science and the Science-Religion Interface," *Journal of Geoscience Education* 58, no. 3 (2009): 178–90; Cindy S. Larson-Miller, "Changing Perceptions of Science in Undergraduate Students: A Mixed Methods Case Study" (PhD diss., Univ. Nebraska, 2011), available online at http://digitalcommons.unl.edu/teachlearnstudent/16.

to use them to predict things.[2] Furthermore, there is a certain breed of physicists, called "string theorists," who have not yet come up with a single testable prediction, but that does not keep them from being classed with the other scientists in the university physics departments where they work.

Even if it isn't easy to come up with a precise definition of "science," however, most people would agree that, in general, science does involve collecting observations about the natural world and coming up with explanations for them that might help us predict or even control the future. Therefore, we could propose a loose definition of science like the following:

> *Science is the modern art of creating stories that explain observations of the natural world and that could be useful for predicting, and possibly even controlling, nature.*

It may bother some readers that we used the word "stories" instead of "explanations," "theories," or "hypotheses" in our definition. It might be a bit shocking to think of science as a kind of "storytelling," because we are accustomed to thinking about science as *factual*, whereas storytelling sounds so *fictional*. After all, people have always told stories to explain natural phenomena—for example, the ancient Greeks explained the daily rising and setting of the sun using the story of Apollo riding his fiery chariot across the sky—but nobody would call such stories "science" in the modern sense. However, we chose the word "stories" to emphasize the idea that the explanations scientists come up with are not themselves facts. Scientific explanations are always subject to change, since any new observations we make might contradict previously established explanations. The universe is a very complicated place, and it is likely that any explanation that humans come up with will be, at best, an approximation of the truth. Albert Einstein emphasized the point that scientific explanations are not facts when he remarked that they are "free creations of the human mind, and are not, however it may seem, uniquely determined by the external world."[3] In other words, scientific explanations are creative products of our minds—stories—not facts that we "discover." A Nobel Prize–winning biologist, Peter Medawar,

2. Samir Okasha, *Philosophy of Science: A Very Short Introduction* (Oxford: Oxford University Press, 2002), 1–2.

3. Albert Einstein and Leopold Infeld, *The Evolution of Physics* (New York: Simon and Schuster, 1966), 31.

explained it even more bluntly. "Scientists are building explanatory structures, *telling stories* which are scrupulously tested to see if they are stories about real life."[4]

Another point that may trouble some readers about our definition of science is that we haven't yet excluded the astrologers. A prominent philosopher of science put it this way: "The difference between science and other enterprises that seek explanations of why things are the way they are can be found in the sorts of standards that science sets itself for what will count as an explanation, a good explanation, and a better explanation."[5] This is not to say that other fields are not effective in explaining certain phenomena, but in order to clarify why scientists do not consider astrology (or history, or philosophy, or any number of other fields of study that could fit our loose definition) as "science," we must explain the kind of standards scientists set for themselves when developing their stories.

Rules for Scientific Storytelling

Just like any literary genre, scientific storytelling follows certain rules that set it apart from other genres. History, historical fiction, realistic fiction, and fantasy, for example, are all types of storytelling that follow different rules regarding how closely bound they must be to the documents, experiences, and artifacts we consider to be acceptable evidence for how life was and really is. And, of course, we have to make rules about what we consider acceptable evidence—whom to believe when sources disagree, when to dismiss eyewitness accounts as impossible, what different kinds of archaeological artifacts mean about how people lived, and so forth. However, it is important to realize that rules are chosen not because no others are possible or because they are infallible guides to "truth" but for convenience in attempting to accomplish certain goals. Remember that science is the art of creating explanations for natural phenomena that could be *useful* for predicting, and possibly controlling, nature. What kinds of rules could be designed to make science more useful in this way?

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4. Peter Medawar, *Pluto's Republic: Incorporating the Art of the Soluble and Induction and Intuition in Scientific Thought* (Oxford: Oxford University Press, 1984), 133, italics in original.

5. Alex Rosenberg, *Philosophy of Science: A Contemporary Introduction* (New York: Routledge, 2000), 21.

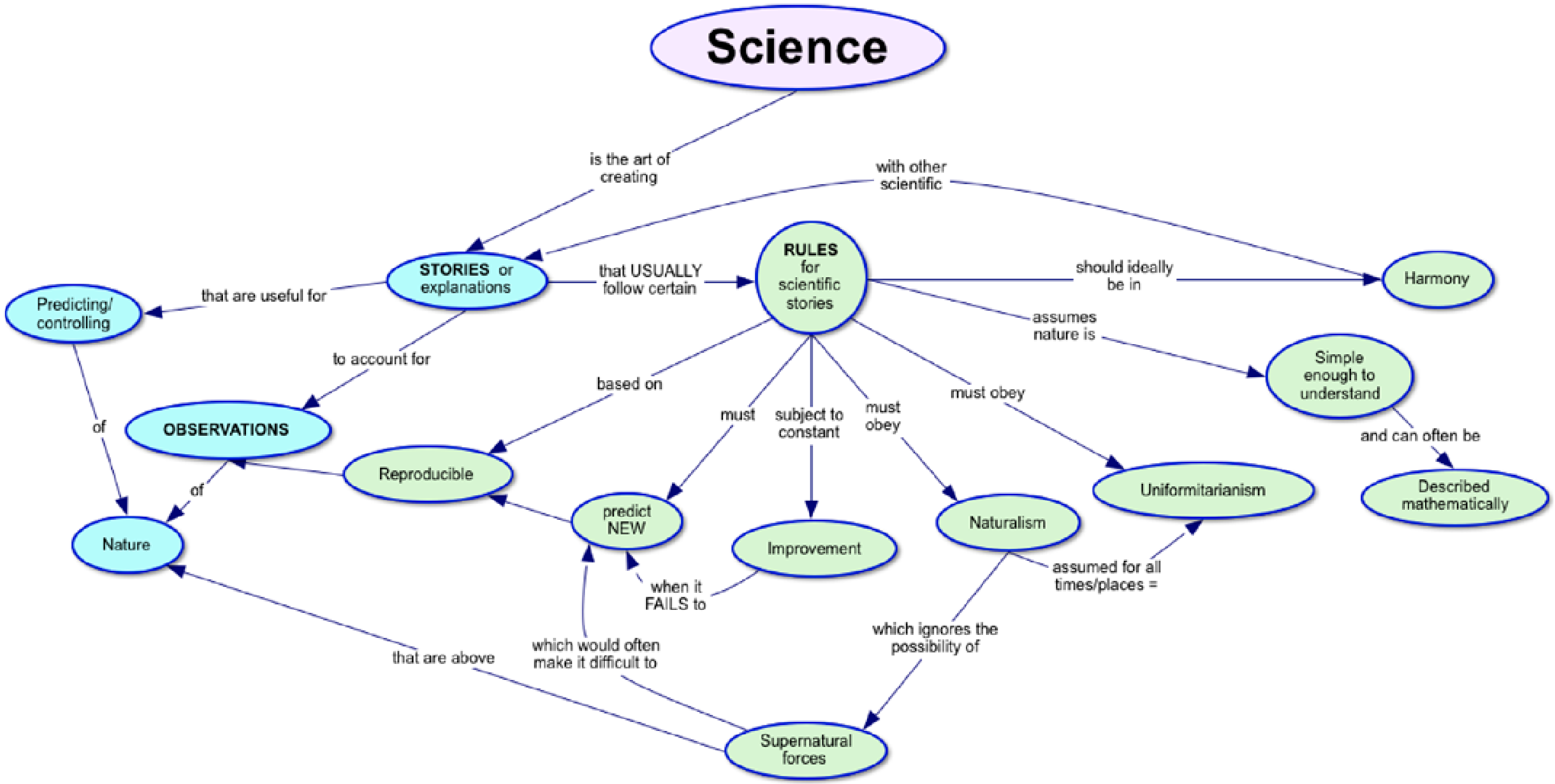

Figure 1. Concept map of the definition of science.

Reproducibility

Our first rule has to do with the kinds of observations that are acceptable as a basis for scientific stories.

> *Rule 1: Scientific stories are crafted to explain observations, but the observations that are used as a basis for these stories must be reproducible.*

For example, a chemist might perform an experiment in her laboratory and make up a story to explain her observations. If this story is to even be considered as a scientific explanation, another chemist should, in principle, be able to make the same observations when performing an identical experiment. (This doesn't mean all these observations actually will be reproduced by other scientists, only that they *could* make the same observations if they wanted to go to the trouble.) If a paleontologist creates a story to explain how life on earth has changed over time, based on fossils he has found in various rock layers, another paleontologist ought to be able to find the same kinds of fossils in those layers. Even an astronomer who observes something strange and fleeting happening in the night sky will immediately call his colleagues at other observatories and ask them to train their telescopes on the same location.

Given that scientific observations are supposed to be reproducible, scientists try to make their observations as carefully as possible. Precise measurements are often very difficult and expensive to make. Scientists are constantly trying to improve the quality of their observations, however, because precise measurements are usually much more difficult to explain. When observations are more difficult to explain, it follows that there are fewer plausible explanations to choose from.

Note well, however, that it isn't the *story* that is reproducible but the *observations* upon which the story is based. One cannot expect our paleontologist to reproduce in some laboratory how life has changed on Earth over millions of years. For one thing, most students would not want to spend such a long time in graduate school.

There are very good practical reasons for this rule—for example, people have been known to be tricked into thinking they see things that aren't really there or even to hallucinate. Sometimes people tend to "see" what they expected or wanted to see, and sometimes they even lie. Should we accept someone's personal experience as "data" that has to be explained by science? Clearly that would open up a can of worms, and most scientists wouldn't want to deal with it.

As practical as this rule is, on the other hand, it is possible that it could be a limitation on science, especially in cases where someone observes something that happens only infrequently. For example, "falling stars" are frequently observed streaking across the night sky, but it is relatively rare for them to be observed in such a way that they can easily be connected with the meteorites that are sometimes found on the ground. In the eighteenth and early nineteenth centuries, reports of "stones falling from heaven" were met with extreme skepticism among scientists because this wasn't possible according to the prevailing theories about the makeup of the heavens. When a meteorite fall was reported by two Harvard scientists, Thomas Jefferson responded, "I could more easily believe that two Yankee professors would lie than that stones would fall from heaven."[6]

In essence, the rule that observations must be reproducible to be "scientific" narrows the field of "facts" that science must explain to experiences that are, in principle, transferable from person to person. Inner religious experiences, strange phenomena that only ever occur to single observers (such as near-death experiences or purported UFO abductions), and even extremely rare (and therefore sparsely attested) phenomena are ruled out as acceptable data for anything but psychological studies. This is not to say that such observations must be hallucinations or lies. Rather, this is simply the scientist's way of dealing with the fact that personal experiences are not always reliable or reproducible.

Predictive Power

Scientific stories are usually called "hypotheses" or "theories." For some people, these words imply that scientific stories have nearly the status of facts, while for others they only imply a hunch or guess. Perhaps the truth lies somewhere in between these extremes, and a more realistic viewpoint can be gained by considering our second rule for scientific stories.

> *Rule 2: Scientists prefer stories that can predict things that were not included in the observations used to create those explanations in the first place.*

When scientists first create a story, they try to explain as many observations as possible. However, there is no way of being sure that they have considered all possible explanations, so these initial stories are

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6. Fletcher G. Watson, *Between the Planets,* rev. ed. (Cambridge, Mass.: Harvard University Press, 1956), 147.

only considered as educated guesses. We call these educated guesses *hypotheses*. A hypothesis is a sort of "*if . . . then*" statement. That is, *if* the explanation is true, *then* certain observations should follow.[7] A good hypothesis will not only explain the observations already collected, but also predict new things that have not been observed. If some of these new predictions can be tested, then we have a way to see if our story can hold up. Once a story has successfully predicted many new observations, scientists start suspecting that it might be on the right track, and start calling it a "theory" instead of a hypothesis. Therefore, even if some scientific stories are guesses, they are at least educated guesses (hypotheses). And even if we cannot really say that scientific stories are the truth, some theories have successfully predicted so many things that we think it is reasonable to believe they are at least on the right track.[8]

Another example should serve to show that the *truth* of a story is not the issue when we are deciding whether a story is *scientific*. In the nineteenth century, the great British scientist Lord Kelvin suggested that the sun might be a glowing ball of liquid, formed as meteorites coalesced by gravitational attraction and generated heat from friction. If this were true, Kelvin reasoned, it ought to be possible to calculate the sun's age, based on estimates of its annual heat loss. He estimated that the sun had been losing heat for a maximum of 100 million years.[9] Further research into the frequencies of light waves emitted by molten meteorites might also have served as a test of the predictive power of Kelvin's story. Now, it turns out that scientists since Kelvin have come up with much better ideas about what the sun is and how its heat is generated, and these new explanations can account for many more observations than Kelvin's. For example, the light waves emitted by the sun are not characteristic of molten meteorites, and radiometric dating techniques seem to support the idea that life has existed on Earth for much longer than 100 million years. In fact, heat generated by radioactivity in the Earth had not been discovered when Kelvin made his calculations, and so he failed to account for it.[10] In other words, Kelvin's explanation is now considered

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7. Eugenie C. Scott, *Evolution vs. Creationism: An Introduction,* 2d ed. (Berkeley: University of California Press, 2004), 12–13.

8. Philip Kitcher, *Science, Truth, and Democracy* (Oxford: Oxford University Press, 2001).

9. William (Lord Kelvin) Thomson, "On the Age of the Sun's Heat," *Macmillan's Magazine* 5 (November 1, 1861): 388–93.

10. Naomi Oreskes, *The Rejection of Continental Drift: Theory and Method in American Earth Science* (Oxford: Oxford University Press, 1999), 48–51.

to be wrong because its predictions failed and because it did not take into account radiogenic heat. However, it is still considered a *scientific* explanation, because it generated predictions that weren't originally used in the creation of the explanation. This kind of prediction allows science to go forward, rather than getting stuck in a rut.[11]

To this end, scientists accord special value to stories that are *mathematically precise*. Lord Kelvin, for example, was able to calculate an absolute upper bound for the age of the sun and posited a relatively precise account of the kind of material from which the sun might be composed. This kind of precision is valuable because it offers a larger target at which other scientists can shoot. In other words, if a story that generates precise, testable predictions happens to be blatantly wrong, it should be relatively easy to shoot it down and move on.

Although some "scientific" explanations don't immediately produce predictions that we can test (remember the "string theorists") and vary widely in degree of precision, it is easy to see why scientists *prefer* precise, testable stories. That is, if we allow too many explanations that cannot be tested in any way, then it becomes harder to decide whether to prefer one story over another.

Prospects for Improvement

In order to fully understand why scientists prefer testable predictions, one must first come to the realization that science is not about establishing "the facts" once and for all, but about a *process* of weeding out bad explanations of the facts we collect and replacing them with better ones.

> *Rule 3: Scientific stories should be subject to an infinitely repeating process of evaluation meant to generate more and more useful stories.*

There is no set method for scientific investigations, contrary to what some people have assumed. Scientists can obtain inspiration for their

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11. Not only that, but prediction becomes part of the success story of science. "The power of prediction," Thomas Huxley wrote, ". . . is commonly regarded as the great prerogative of physical science." Thomas H. Huxley, *Science and Hebrew Tradition* (New York: D. Appleton, 1903), 10. What he had in mind is that scientific prediction is widely regarded as much more reliable than, say, religious prophecy or psychic precognition. One need only recall the public surprise that accompanied the 1758 appearance of Halley's Comet. Comets had always elicited wonderment, but this time much of the wonderment stemmed from the *accuracy* of Edmond Halley's prediction, which enhanced the status of Newtonian science.

stories in any number of ways, all of which involve considerable creativity, inspiration, or blind luck, and it isn't always clear by reason alone which of a number of competing stories should be favored. However, a basic process for much of what passes for "science" can be outlined as follows.

1. Scientists make observations about the natural world.
2. Scientists come up with explanations that can explain these observations, or at least the ones that we are most sure about, or seem most important.
3. Other consequences of these explanations are evaluated, and scientists come up with ways to observe whether some of those predictions are true.
4. Scientists then make these other observations to test their predictions.
5. If the predictions work out, then the original explanation may be kept. If the predictions do not work out, then scientists do one of three things.
   a. They throw out their initial explanation and try to come up with another one that explains all (or at least most) of their relevant observations.
   b. They slightly modify their original explanation to account for the new observations.
   c. They ignore the new observations that do not fit with their explanation, assuming there must be something wrong with the observations. Then they either go on as if nothing had happened or try to improve the observations.
6. Whether they keep the original explanation or go with another one, scientists always return at this point to step 3 and keep repeating steps 3 through 6 over and over again.

The hope is that following this iterative process will help scientists come up with better and better stories to explain the natural world. What do we mean by "better"? In general, a better story explains more observations or generates more predictions. In other words, it is more useful and amenable to further testing. Other factors may be involved, however. For instance, a scientist may prefer one theory over another because it seems more simple, or elegant. Sometimes scientists give greater credence to observations that were collected by scientists with whom they are personally familiar or who come from the same country.[12] Thus, scientists should never assume that their favorite stories represent "the truth," because one can never tell whether an even better explanation will pop up next week. However, by tying their stories to real observations of the natural world, scientists hope to at least come up with explanations that are *realistic*, even if they are not exact representations of reality. They try to make their stories progressively "less wrong," even if they can never tell when they have gotten them exactly right.[13]

Indeed, we claimed above that scientists are perfectly capable of ignoring observations that conflict with their established explanations. Why would they do such a thing? The fact is that sometimes observations go wrong—instruments do not work correctly, experiments are contaminated, and people can be deceived in what they think they see. Furthermore, the world is a complicated place, and even if a few observations seem to conflict with an explanation, it may still be mainly correct. And if it isn't immediately apparent how to fix the theory, that's no reason to throw out an otherwise perfectly good explanation. However, if observations that don't fit a scientific story keep piling up rather than being successfully explained away, scientists begin wondering whether they ought to look harder for a better story.[14]

Consider the example of Galileo Galilei (1564–1642). In his time, the geocentric (Earth at the center of the universe) astronomy that was in fashion at the time was in trouble—a number of observations were very difficult to explain with this kind of theory. To overcome some of these problems, Copernicus had proposed that the sun is at the center of the universe, and everything else revolves around it in circular orbits. Galileo used a telescope to produce observations that he then advertised as supporting the Copernican theory. For example, he could show that the brightness of the planets changed throughout the year, which was predicted from the Copernican idea that the Earth should be at different distances from the planets at different times of year. However, the magnitudes of some of these variations were not nearly large enough to be explained by Copernicus's model. Also, many people who looked through Galileo's telescope distrusted it, because although it seemed to work well

12. Oreskes, *Rejection of Continental Drift,* 51–53.

13. Paul Grobstein, "Revisiting Science in Culture: Science as Story Telling and Story Revising," *Journal of Research Practice* 1, no. 1 (2005): article M1.

14. Thomas S. Kuhn, *The Structure of Scientific Revolutions,* 3d ed. (Chicago: University of Chicago Press, 1970).

when pointed at objects on the Earth, optical illusions (such as double vision) were noted when it was pointed toward the heavens.[15]

Clearly, the Copernican theory had problems of its own, and many of them were not solved for decades, or even centuries, as the Copernican theory was adjusted to accommodate things like elliptical rather than circular orbits and better theories of optics were developed. So why did it quickly become the dominant explanation of the motion of heavenly bodies, even in the face of contradictory evidence? Perhaps the answer is that even if the Copernican theory had problems, its adherents saw the *general idea* of a sun-centered universe as more promising than the idea of an Earth-centered universe, and so they were willing to try to work out those problems. It turns out that in this case their hunch was right, and even if our ideas about how the universe is structured are now quite a bit different than the Copernican model, we can look back and say that the Copernicans had one or two key ideas that turned out to be indispensable.

The idea that we hope to get across here is that, at least in our opinion, the way scientists generate and improve their stories is quite reasonable, even if it isn't exact and involves considerable guesswork. We certainly can't expect this kind of method to generate "absolute truth" on the first, second, third, or millionth try. But when we constantly try to improve our stories by testing and altering them to accommodate more observations, they are pretty much guaranteed to become more "useful." And as they become more and more successful at explaining and predicting more and more things, we at least have some justification for suspecting that they do have some connection with the ultimate truth about how things work.

Naturalism

The kind of human limitations just discussed are not the end of the story, however. It turns out that scientists also deliberately impose certain limitations on their craft for practical reasons, even beyond the limitation that observations be reproducible.

> *Rule 4: Scientific explanations do not appeal to the supernatural. Only naturalistic explanations are allowed.*

When we speak of "naturalistic" explanations, we mean explanations that appeal only to "laws of nature" that operate in a regular fashion. For example, unsupported objects near the surface of the earth always

15. Paul Feyerabend, *Against Method,* 3d ed. (New York: Verso, 1993), 86–105.

seem to fall downward. We can use this "law of nature" to explain many things, including the directions in which rivers travel, the transport of sediment toward the ocean, and so forth. On the other hand, "supernatural" explanations appeal to the possibility that there might be forces above the "laws of nature" that can suspend those laws. For example, we might call the observation that people die and their bodies decay a "law of nature," but the Christian New Testament explains the claimed sightings of Jesus after his death by teaching that Jesus was resurrected. If this really happened, it seems unlikely to have been the result of the everyday operations of "laws of nature."

Looking back to some of the examples already discussed, it is clear that the explanation of the sun that included the Greek god Apollo is ruled out from the start, whereas Kelvin's explanation is not. Whereas the Apollo story involves a supernatural being, Kelvin appealed only to natural causes, such as the gravitational attraction between meteors and heat generation by friction. He said he favored his explanation of the sun's heat because "no other natural explanation . . . can be conceived."[16]

This distinction brings us to a rather odd problem. That is, many scientists believe in Judaeo-Christian, Muslim, and other concepts of God and spirituality along with most of the rest of the world. Many of them even believe that "supernatural" events have occurred. And yet by the year 1800, it was very rare for scientists to introduce the supernatural into scientific explanations; today it is essentially unheard of.[17] For example, Lord Kelvin not only believed in a Christian concept of God, but he even used his estimate of the age of the sun to show that there could not possibly have been enough time for life on Earth to have evolved from lower forms, as Charles Darwin suggested. He went on to propose that a relatively young solar system ruled out organic evolution, and this, in turn, implied an intelligent Creator. Here he did not use the supernatural to *explain* how life on Earth appeared—he merely argued that the naturalistic explanations that had been proposed so far were deficient. And yet Kelvin used a naturalistic explanation of the sun to make his argument. If Kelvin believed that God supernaturally generated life on earth, then why would he feel compelled to stick to "natural" explanations when offering a scientific account of the origin of the sun?

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16. Thomson, "On the Age of the Sun's Heat," 393.

17. Edward B. Davis and Robin Collins, "Scientific Naturalism," in *Science and Religion: A Historical Introduction,* ed. G. B. Ferngren (Baltimore: Johns Hopkins University Press, 2002), 322–34.

There are three practical reasons for sticking to naturalistic explanations in science. First, supernatural explanations tend not to generate precise new predictions. Not only does this stop the scientific enterprise in its tracks, but it also isn't very useful. That is, supposing the sun is Apollo's chariot, what can we then do with that information? The stories about Apollo do not specify whether his horses leave giant droppings or anything else that might help us determine whether this explanation of the sun is any more likely than others. Science operates by observing *regularities* in nature, but supernatural beings like Apollo might decide to change the natural order at any moment, and how could we predict when or why that would happen? Second, it is usually very difficult to place limits on which supernatural explanations are acceptable. For example, if it is acceptable to say that the sun is Apollo's chariot, then why not Odin's shiny helmet?

Both of these points can be overstated, however. It might well be possible for supernatural explanations to generate new predictions—even some that could easily be tested—but in order for this to be so, we usually must know something in advance about the supernatural agent in question. For example, if we say that God created the world, we can generate predictions about what the world is like only if we know something about what God *could have* and *would have* done during the Creation. And this brings us to our third reason for sticking to naturalistic explanations. Different groups ascribe different attributes to God and other supernatural agents, so if we allowed supernatural explanations in science, we would end up with various versions of Christian, Muslim, Hindu, Buddhist, and Jewish science, to name but a few. In a pluralistic society, and in an age when science is a big-money, publicly funded enterprise, most scientists would prefer that we all just try to come to some sort of compromise, for the moment, and that compromise entails keeping the supernatural out of scientific stories.[18]

Another example of the usefulness of a naturalistic approach to science is the story of the ancient Greek physician Hippocrates. In Hippocrates' day, illness was often attributed to the anger of the gods and other such causes. In that case, a physician's job was to invoke the aid of the gods (usually Asclepius, Apollo's son) to heal the sick person.

18. It should be acknowledged that this convention in science to exclude all but naturalistic approaches has contributed to a spreading secularism in society since science tends to influence many other disciplines as well as modern culture in general.

Hippocrates challenged this practice, not because he did not believe in the gods, but because he thought that the physicians of his day were often using the gods as an excuse for their own ignorance of the causes of disease. If, on the other hand, diseases were *mostly* the result of natural causes, one might often find natural cures.[19] This sort of pragmatic attitude is very common today, even among deeply religious people. That is, when people are seriously ill, they usually check into a hospital, even though they might also pray for divine help.

On the other hand, even if the supernatural isn't allowed in scientific explanations, individual scientists may still use their religious views or other inner experiences in the creative process. For instance, Albert Einstein frequently mused about how "the Old Man" (referring to his impersonal concept of God) would have done things. However, when it came to his published scientific explanations, "the Old Man" never made an appearance. The Belgian scientist Friedrich Kekulé hit upon the idea that the benzene molecule has a hexagonal (or ringlike) structure after he had a dream in which a snake tried to swallow its own tail, but he went on to test this idea using scientific methods.[20] After recounting a "child-like thought experiment" that led to his special theory of relativity, Einstein explained, "Discovery is not a work of logical thought, even if the final product is bound in logical form."[21] In the creative process, anything goes, so long as a naturalistic and logical account can be given later.

It should be remembered that scientists exclude God and other supernatural agents from their stories *only* because there are practical reasons to do so, and not because they necessarily must. Furthermore, just because they can come up with a naturalistic explanation for something, it doesn't follow that the explanation is *true*. As discussed above, we can never be sure that we have hit upon the one and only possible explanation for our observations, and we can never be sure that more observations will not contradict our stories.

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19. Richard E. Rubenstein, *Aristotle's Children: How Christians, Muslims, and Jews Rediscovered Ancient Wisdom and Illuminated the Middle Ages* (Orlando, Fla.: Harcourt, 2003).

20. Okasha, *Philosophy of Science,* 79.

21. Albert Einstein, "Autobiographische Skizze," in *Helle Zeit—Dunkle Zeit*, ed. Carl Seelig (Zurich: Europa Verlag, 1956), 10, cited in John D. Norton, "Chasing the Light: Einstein's Most Famous Thought Experiment," in *Thought Experiments in Philosophy, Science, and the Arts,* ed. Mélanie Frappier, Letitia Meynell, and James Robert Brown (New York: Routledge, 2013), 130.

Once these points are clear, it should be apparent that once in a while there will be conflicts between science and various religious viewpoints. If we do not allow the supernatural to play any part in scientific explanations, how can we expect them to always be in harmony with religious philosophies that specifically claim there are supernatural influences on the natural order? Occasional conflicts would seem to be inevitable, and therefore such conflicts should not come as a shock to anyone.

Uniformitarianism

Most people will agree that *most of the time* the world operates in a regular manner, according to some natural laws. Therefore, they have little problem with most science as it is now practiced. On the other hand, some people believe that this has not always been the case in the past. For example, some people believe that God created the world out of nothing in the not-too-distant past and that other "miracles" occurred in the past. This poses a problem for the "historical sciences"—those that interpret the present state of things in terms of past events. For example, consider the popular TV series *CSI*. In this show, crime scene investigators (forensic scientists) examine the details of a crime scene (blood spatter patterns, angles of bullet holes, objects that seem out of place, injuries evident on a dead body, and so on) and make up stories about how the present situation might have come about. In order to test their stories, they might shoot bullets into Jell-O, try to mimic the production of blood spatters, use trigonometry to determine from where a bullet might have come, and that sort of thing. The assumption implicit in all of these activities is that the crime scene reached its present state via processes that can be mimicked in the laboratory. They do not even consider the possibility that some supernatural entity might have been involved. Why? Because if they admitted such a possibility, all their normal methods for evaluating evidence would go out the window. Furthermore, when the case reaches the courtroom, even juries packed with deeply religious people tend not to listen to pleas by defense attorneys that supernatural entities adjusted crime scenes to make the defendants look guilty. This brings us to our next rule.

> *Rule 5: Any scientific explanation involving events in the past must square with the principle of "uniformitarianism"—the assumption that past events can be explained in terms of the "natural laws" that apply today.*

How do we explain the presence of certain mountains that have a definite cone shape and are otherwise similar (in rock type and other features) to active volcanoes? The active volcanoes we know today spew out ash and lava, building on top of themselves to make a cone shape. Is it not reasonable to suggest that perhaps our mysterious cone-shaped mountains are extinct volcanoes? Consider fossils. They look like the remains of living things. Is it not reasonable to suppose that they were once living things that were covered and preserved in sediment, just as dead organisms can be covered and preserved in sediment nowadays? The idea here is *not* that everything has always been the same in every respect or that catastrophic, out-of-the-ordinary events never happen. For example, many scientists believe that an asteroid impact led to the extinction of the dinosaurs. Rather, the idea is that the same "laws of nature" have always been in effect. Astronomers track the motions of asteroids whizzing around the solar system today, and they don't have to invoke the supernatural to suppose that a large asteroid might hit the Earth every once in a while.

Once again, this is something we cannot know in any absolute sense, because we cannot travel back into the past to verify it. And even if we could travel back into the past, we certainly could not verify that the laws of nature have always operated in the same way at every moment and in every location in the past. Furthermore, we may well discover new "laws of nature" in the future that we have never noticed before or discover that some of the laws familiar to us have exceptions.

We already mentioned that there could be supernatural agents who change how nature operates from time to time, and, in fact, many people (including some scientists) believe that this has happened on occasion. Why would scientists, even those who do not believe it, make the assumption of uniformitarianism if it can never really be verified? This question can be answered by asking what would happen if scientists assumed the opposite—that for whatever reason, the laws of nature do not always operate in the same way. In that case, how could they explain any past events? Scientists draw inferences from *regularities* they observe in nature. Therefore, if they were to assume that these regularities did not operate in the same way in the past, science would have to be shut down, at least with respect to explanations involving past events. Again, scientists make this assumption as part of the cost of doing business, rather than because they are sure it is always true. Even if it is only true *most* of the time, such an assumption is probably worthwhile.

This kind of thinking is completely normal, both in science and in everyday life. For example, when scientists perform calculations to predict the gravitational attraction between the Earth and other objects in space, they routinely assume that the Earth is spherical. They know perfectly well that the Earth isn't actually spherical—it is slightly squashed on two sides, and somewhat lumpy. However, the assumption that the

Earth is spherical makes the math involved in the calculation so much more simple that the problem becomes easily solvable, and the answers we obtain are not very far off from those we would have gotten otherwise. As another example, consider the behavior of people who live in earthquake-prone areas. They get up and go to work, assuming all the while that no major earthquakes will occur that day, and yet they know in some corner of their minds that "the big one" might happen any time. They assume something that they know might not be true because their assumption will likely be true most of the time.

Simplicity

Another practical assumption is embodied in our next rule. Once again, it is the kind of assumption that must be made in order for science to keep operating.

> *Rule 6: Scientists assume that nature is simple enough for human minds to understand.*

The assumption of simplicity seems rather arrogant, doesn't it? After all, if humans are a small part of the natural order, how can our tiny brains ever comprehend the whole? Once again, we will not have to look far to find scientists who do not actually believe in this principle, or at least recognize it as unprovable,[22] so why do they make this assumption anyway? If they assumed that nature is *not* simple enough for the human mind to understand, scientists would have to give up on all their attempts to understand things. Therefore, even if the truth is that humans are capable of understanding nature only in a very limited way, it is immensely practical to make the assumption of simplicity.

This rule could be considered a rather obvious point and not directly related to the art of scientific storytelling. However, the assumption of simplicity implies something very important about scientific stories—that is, if nature is *understandable*, then we can come up with correct *explanations* for phenomena, and not just accurate *descriptions*. It is possible to make scientific stories that are more descriptive than explanatory, but the fact is that scientists value explanations more than descriptions. For example, Sir Isaac Newton created a simple, yet amazingly accurate mathematical equation to describe the force of gravitational attraction

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22. Okasha, *Philosophy of Science,* 58–76; Naomi Oreskes, Kristin Shrader-Frechette, and Kenneth Belitz, "Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences," *Science* 263, no. 5147 (1994): 641–46.

between objects, but he could not explain why such a force that acts at a distance should exist. Many of his fellow scientists were very uncomfortable with this and called gravity an "occult" force.[23] If scientists were content merely with description rather than explanation, perhaps the idea of "action at a distance" wouldn't have caused such a stir. However, the search for an explanation for gravity was continued, and eventually Albert Einstein showed that gravitational attraction could be explained as an effect of the curvature of space-time around massive objects.

If some readers are wondering what "the curvature of space-time" might mean, then it is an opportune time to point out another fact about the assumption of simplicity. Namely, even though scientists assume nature is simple enough to understand, it does not follow that nature adheres to what we might call "common sense." The fact is that people don't usually form "common sense" judgments about things based on very careful observations, and when we force ourselves to observe carefully, it often turns out that reality doesn't conform to our expectations. For instance, the ancient Greek philosopher Aristotle explained that earthly objects fall downward because their natural place is on the earth, whereas fire goes upward because its natural place is in the heavens. This is a good "common sense" story that actually explains quite a bit of what people observe on an everyday basis. However, when more careful observations were made about the acceleration of falling bodies, the motion of the planets, and so on, it soon became clear that Aristotle's physics could not do the job. The physics of Newton and Einstein were successive attempts to explain more and more careful observations that conflicted with a "common sense" view of the world.[24]

Therefore, even if nature is simple enough to understand, it does not follow that we can really understand it without an awful lot of hard work and creativity.

Harmony

Scientists generally want people to accept their stories and make use of them, but most people would hesitate to do so if they could see that different scientific explanations contradicted one another at every turn. Even if we can never be sure our explanations are correct, we don't want them to be a mass of confusion.

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23. Rosenberg, *Philosophy of Science,* 82–83.

24. Lewis Wolpert, *The Unnatural Nature of Science: Why Science Does Not Make (Common) Sense* (Cambridge, Mass.: Harvard University Press, 1992).

Rule 7: Scientific explanations should not contradict other established scientific explanations, unless absolutely necessary.

This last rule illustrates something truly grand and wonderful about science. That is, millions of scientists are continually working on creating their stories about various aspects of nature, but these should ideally not be a contradictory mass of confusion. Lord Kelvin, for example, connected his explanation of the sun to well-established principles like gravity and Joule's experiments involving motion and heat. The goal is to make one big story with a coherent plot from the millions of little stories scientists create.

Once again, when we look closely we find that scientific stories do not always fit perfectly together. However, it is by trying to resolve contradictions between different stories, and between scientific stories and observations, that scientists make progress.

This principle illustrates the fact that science really is a community endeavor. People often have the idea that big scientific advances occur when lone geniuses buck the consensus and put forward bold new ideas. There is some truth to that notion, but in fact these new ideas probably wouldn't make it very far without the rest of the scientific community. When it comes to making up a substantially different new story that explains all the relevant observations and harmonizes with other established scientific stories, it is usually just too hard for anyone to do alone.

Galileo Galilei, for example, put forward a number of good physical arguments for Copernicus's theory that the Earth and the other planets revolve in circular orbits around the sun. As we discussed above, however, there is always more than one possible explanation for any set of facts, and Galileo acknowledged that there were ways those who thought the Earth was at the center of the universe could modify their views in minor ways to explain some of the same phenomena. He thought he had one argument that was conclusive, though. This argument is too complex to recount in detail here, but in a nutshell, Galileo thought that the kind of motion posited by Copernicus for the Earth could explain the tides. If Copernicus were correct, the oceans should slosh back and forth once per day. But as others pointed out, in most places the tides go in and out twice per day. To the end of his life, Galileo held on to this argument, even though it was plainly contradicted by observation.[25]

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25. W. R. J. Shea, "Galileo's Claim to Fame: The Proof That the Earth Moves from the Evidence of the Tides," *British Journal for the History of Science* 5

None of this should be taken to mean that Galileo wasn't really a great scientist or that we shouldn't honor his lasting achievements. Even if he didn't get everything right, Galileo did exactly what good scientists do—he published his arguments so that others could read and criticize them. Nowadays, the norm is for scientists to publish their work in "peer-reviewed" journals. They send in a manuscript to the journal office, and the editors send it out to anonymous, expert reviewers, who pick it apart to find any obvious errors or bad arguments. If the manuscript isn't rejected outright, the authors must address the reviewers' concerns before it can be published. The reviewers' criticisms aren't always right, and they don't always catch all the problems, but subjecting scientific ideas to this kind of examination works well to encourage improvement and makes up for some of the personal foibles of the people involved. This is why the requirement to share data and ideas is one of the hallmarks of modern science, in contrast to many earlier systems of knowledge.[26]

The winnowing process doesn't stop once a scientific paper is published. Others then have a chance to study the data and ideas presented and to produce their own, which might reinforce, contradict, expand, or modify what has come before. Think of it as a conversation that goes on indefinitely, gradually changing topics as the parties involved reach agreement, and sometimes revisiting old topics when new information becomes available.

Even if the door is always open to revisit scientific conclusions, the conversation does tend to move on. But how? Two prominent science historians put it this way: "History shows us clearly that science does not provide certainty. It does not provide proof. It only provides the consensus of experts, based on the organized accumulation and scrutiny of evidence."[27] In a scientific context, achieving "consensus" rarely, if ever, means that 100 percent of the experts agree. As we just saw, even great scientists like Galileo can sometimes dogmatically hold on to faulty arguments. Even if nearly all the experts are convinced of a particular scientific story, it may turn out to be wrong in important respects.

(December 1970): 111–27.

26. Robert K. Merton, *The Sociology of Science: Theoretical and Empirical Investigations* (Chicago: University of Chicago Press, 1973), 274.

27. Naomi Oreskes and Erik M. Conway, *Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming* (New York: Bloomsbury Press, 2010), 268.

Nevertheless, if we want to talk about which parts of scientific stories are "settled" in some sense, the consensus of experts is all we have.

This distinction is especially important when the public looks to scientists for guidance about policy issues. If we are trying to decide whether to restrict tobacco smoking or cut down on greenhouse gas emissions, for example, we generally want to base such decisions at least partially on what science tells us about the dangers of secondhand smoke and human impacts on the climate system. It is all too easy to find a handful of experts on any issue who will disagree even with an overwhelming consensus of their colleagues. They could be right, or they could (more likely) be wrong. Expert opinion is not altogether immune to political pressures or considerations such as the source of research funding. One reasonable response to these dilemmas would be for everyone to become experts on these issues themselves, but most of us simply don't have the time to put in the necessary work. Another reasonable response would be to determine the extent to which there is an expert consensus, and go with the majority. Perhaps there are other reasonable responses, but in a realm where absolute certainty and proof do not exist, "reasonable" is often the best we can do.

Conclusions

Clearly, science is not solely about discovering "facts" about the natural world, although scientists do spend a lot of time making observations and conducting experiments. Rather, the real essence of science is *storytelling*—creatively making up stories to *explain* what we observe in the natural world. But how is science different from other kinds of attempts to understand the world? We have listed a few rules of thumb to help make this distinction, but in some cases these rules have clear exceptions. For example, scientific stories aren't always immediately testable, and therefore aren't always amenable to the constant winnowing process that scientists employ. They also don't always mesh perfectly with other established scientific explanations. However, scientists clearly place a much higher value on stories that make precise, testable predictions about the natural world and mesh well with the other stories scientists tell. This *value system*, more than anything else, is what makes modern science so powerful. If scientists place more value on stories that predict new things, then the best scientific stories are the ones that are put at the greatest risk of failure. And when they do fail, scientists eventually try to find and fix the problems, leading to even more powerful stories. Similarly, the warning flags that go up when a scientific story doesn't mesh well with others can lead to more progress as scientists try to resolve the apparent contradictions. By constantly subjecting their stories to this kind of scrutiny, scientists try to make their stories *realistic,* even if we can never tell whether we have hit upon a completely true description of reality.

However, some of the rules explained here represent unprovable assumptions that scientists adopt in order to make the problems they tackle in some sense solvable. If there really were supernatural entities that sometimes alter the natural order, science would be blind to that fact. If nature were really too complex for the human brain to comprehend, science would ignore it. In some other fields of inquiry (such as religion or philosophy), we can ask "why" things happen, or what "ought" to be done, but not in science. Science can help us control powerful processes like nuclear fission but cannot tell us whether to use them for peaceful or warlike purposes. Indeed, scientists mostly limit their stories to explaining only those observations that are reproducible, and this sometimes might exclude aspects of reality that are not easily transferable from one person to another. Therefore, science is a powerful, but limited, path to understanding.

When more people see science for what it is—a powerful yet limited and thoroughly human enterprise—it is our hope that they will make more informed judgments about where scientific stories should fit in their own lives and in contemporary society.

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