CH 1: WHAT IS SCIENCE? REV 1

Imagine for a moment that you were an extraterrestrial approaching the planet Earth for the first time. What would you notice?

There are lots of candidates for answers to this question. You might, for example, exclaim over the presence of liquid water on the planet's surface—a rare phenomenon in the universe. You might wonder why the atmosphere was full of a corrosive, poisonous gas that the natives called oxygen. But my guess is that you would notice something else. Among the life forms present, you would notice that one species—the one that calls itself *Homo sapiens*—is somehow different. Alone among the millions of living things on the planet, this species has spread over the entire habitable surface, converted vast tracts of forest and grassland to farms, and built an interconnecting grid of massive cities. It has dammed rivers, built highways, and even come to dominate some of the natural chemical cycles that operate in the planet's ecosystems. While closely related to all the other life forms at the molecular level, this species is just….well…. different.

Why?

I would suggest that the answer to this question lies in one simple fact. Human beings are the only life form on Earth that has developed a method that allows them to understand the universe around them (what we call science) and the ability to use that understanding to transform the environment to their advantage (what we call technology). It is these twin abilities, developed over millennia, that have allowed humanity to prosper as it has.

In fact, I will go so far as to argue that the really deep changes in the human condition – the ones that produce fundamental differences in our world—arise because of advances in science and technology. Let me give you two examples to back up this claim.

Forty thousand years ago our ancestors eked out a fragile existence as hunter gatherers, harvesting the food that nature provided for them. Then, over a long period of trial and error culminating around 8000 BCE, some of them (probably mostly women) discovered that life didn't have to be lived that way. They observed the way that wild plants grew and realized that instead of being satisfied with what nature offered in the way of nourishment, they could plant seeds, tend the growing crops, and harvest the final product. The enterprise we call agriculture was born and the world has never been the same. The surplus of food allowed human beings to begin building cities, where arts and learning could grow. To be fair, it also allowed for the existence of standing armies, another, perhaps less welcome, aspect of modern life. But in any case, those early farmers, without writing, mostly without metal tools, used their observations of the world to change it forever.

Fast forward ten thousand years, to England in the latter half of the eighteenth century. This was a country poised to become the greatest empire the world had ever seen, a country with enormous social and class inequalities, and one whose major colony in North America was on the brink of declaring independence. Suppose you imagine yourself in London in 1776 and ask a simple question: what is going on in this country that will have the greatest impact on human life over the next couple of centuries?

I would suggest that if you wanted to answer this question you wouldn't go to the great universities or to the seats of government. Instead, you would go to a small factory near Birmingham, to the firm of Watt and Boulton, where the Scottish engineer James Watt was perfecting his design of the modern steam engine.

A word of background: there were steam engines in existence before Watt, but they were cumbersome, inefficient things. A two story high engine, for example, developed less power than a modern chain saw. What Watt did was to take this cumbersome device and change it into a compact, useable machine.

Seen in retrospect, this was a monumental advance. For all of human history the main source of energy had been muscles—either animal or human—with small contributions from windmills and water wheels. Suddenly, the solar energy that came to Earth hundreds of millions of years ago became available, because it was trapped in the coal that was burned in Watt's steam engine. This engine powered the factories that drove the Industrial Revolution, the railroads that tied together continents, the cities where a greater and greater proportion of humanity spent their lives. The machines being built in that grubby factory were the agents of a fundamental change in the human condition. And whether you think this is a good thing (as I do) or a deplorable one (as has become fashionable in some circles), you can't deny that it happened.

Science and Technology

In this book we will look at a number of other discoveries and developments that have had (or are having) the same sort of deep effect. The development of the electrical generator transformed the twentieth century, breaking forever the ancient link between the place where energy is generated and the place where it is used. The germ theory of disease changed the way medicine was done, producing unheard of lifespans in the developed world. The development of the science of quantum mechanics led to the digital computer and the information revolution that is transforming your life even as you read these words.

While it is indisputable that science and technology have changed our lives, we need to understand the differences between the two of them. In everyday speech they have come to be used almost interchangeably, but there are important distinctions that need to be made. As implied in the previous discussion, science is the quest for knowledge about the world we live in, technology the application of that knowledge to satisfying human needs. The boundaries between these two activities are fuzzy at best, with large areas of overlap—indeed, we will spend a good portion of Ch(00) exploring in detail the process by which abstract knowledge is turned into useful devices. For the moment, however, we should just keep in mind the notion that these two terms refer to different sorts of processes.

Science and technology, then, go a long way toward explaining what the hypothetical extraterrestrial with which we started the discussion would observe. And this, of course, leads us to a number of interesting questions: what exactly is science, and how did it arise How similar to modern science was the work of previous civilization, and in what ways did their approaches differ from our own and from each other? Are there any activities that are common to every scientific endeavor? Before we get into a detailed description of the way that science is practiced in the 21st century, let's look at these historical questions.

The Historical Question

Later in this chapter we will describe the modern full blown scientific method in some detail, but for the moment we can picture it as a never ending cycle in which we observe the world, extract regularities from those observations, create a theory that explains those regularities, use the theory to make predictions, and then observe the world to see if those predictions are borne out. In simple diagrammatic form, we can picture the normal modern scientific method as a clockwise cycle

Observation

Prediction Regularity

Theory

One way of asking the historical question, then, is to ask what parts of this cycle various civilizations of the past used. The first two steps—observation of the world and the recognition of regularities—are pretty universal, and probably predate the appearance of *Homo sapiens* on the evolutionary scene. No hunting-gathering group would last very long if its members didn't know when fish would be running in a particular stream or nuts would be ripening in a particular forest. Indeed, we will argue in the next chapter that many pre-literate civilizations developed a rather sophisticated astronomy based on regular observations of the sky. The existence of structures like Stonehenge in England and the Medicine Wheels of western North America testify to this sort of development. An important lesson we learn from these sorts of structures is that it is possible to pass complex information about the natural world from generation to generation through the oral tradition, even in the absence of writing.

The absence of written records make it difficult to know what, if any, theories these early peoples developed to explain what they saw. This situation changes when we look at the civilizations of Mesopotamia and Egypt. Here we run into a strange dichotomy. The Babylonians kept the best astronomical records in the ancient world—in fact, their data was still being used by Greek astronomers centuries after it was recorded. As far as we can tell, however, they seemed totally uninterested producing a theory to explain their findings. It seems that if they were able to look at the data and figure out when the next eclipse would occur, they were satisfied. In terms of the cycle pictured above, they seemed to get off the train with regularities and not be interested in going any further.

The Egyptians aremore typical. They told stories about what they saw in the sky, explaining the motion of the heavenly bodies in terms of the adventures of the gods. Whether this sort of explanation of nature constitutes a ‘theory’ is a tricky question, depending as it does on how you define the word “theory”. The point, however, is that once you explain any natural phenomenon in terms of the whims of the gods, you lose the power to make real predictions, since in principle those whims can change at any time. In this case, you are limited, as were the Babylonians, to relying on past regularities to forecast the future. As far as we can tell, this was the case for most of the advanced ancient societies we’ll be studying.

The people who broke out of this mold were the Greek natural philosophers, who first began to construct theories based on purely naturalistic explanations of the world. By the first century CE, in fact, natural philosophers in Alexandria had put together a marvelously complex model of the solar system capable of making rudimentary predictions about things like eclipses, the rising and setting of the planets, and the time of the new moon.

During what are called the Middle Ages in Europe, the center of gravity for the development of science moved to the Islamic world (see Ch(000)) and progress was made in many area—we will look specifically at mathematics, medicine, and astronomy. If you had to pick a date for the development of the modern scientific process, however, you would probably talk about the work of Isaac Newton in England in the 17th century (see Ch(000)). This is when the full blown scientific method outlined above made its appearance—the time when we went ‘all the way around the cycle’.

Modern scientists tend to reserve the work ‘science’ for the development that started with Newton (or, sometimes, with Galileo some decades earlier). In essence, they tend to regard what came before as a kind of ‘pre-science’. Since this is common usage among my colleagues, I will use it, but in what follows I would urge you to keep in mind that one of the greatest failings of those who study history is to judge the past by the standards of the present. To my mind, the illiterate men and woman responsible for Stonehenge were every bit as good a set of ‘scientists’ as my colleagues in any university science department of which I’ve been a member. The proper question to ask is not “How close did this ancient civilization come to what we do today?” but “What did they do and how did it fit in to their cultural life?”

Having said this, however, the modern scientific method can serve as a useful template that will help us organize the accomplishments of the various ancient civilizations we will study. It is useful, therefore, to examine this method in its current form, a subject to which we will devote the rest of this chapter

The Modern Scientific Method

Before we launch into this subject, I want to make a strong caveat—one that I will emphasize at the end of the chapter as well. Science is a human endeavor, carried out by human beings no different from the rest of us. One well known characteristic of human behavior is an aversion to blindly following rules. Like artists and musicians, scientists often delight in departing from the path of tradition and striking out on their own. Thus, what follows should be thought of as a list of elements found in most scientific work, more or less in the order in which they can normally be expected to appear. It should not be thought of as a kind of 'cookbook' that all scientists follow at all times.

Observation

All science begins with observation of the world. It is important to point out that the idea that you can learn about the world by observing it, an obvious proposition to those of us living in secular, technology driven societies, has not been a universal given throughout most of human history. There are, in fact, many ways of approaching the problem of learning about the universe. In Ch (00), for example, we will talk about the approach taken by many Greek philosophers, an approach in which the power of human reason, rather than observation, was the main tool for exploration.

We can see another way of approaching the world in the seemingly endless debate about the inclusion of creationism (or its latest incarnation, intelligent design) in the science curriculum in American public schools. On one side of this debate is the scientific community, relying on data gathered from the fossil record and modern measurements of DNA – data gathered, in other words, through observations of the world. On the other side we have people for whom a literal interpretation of the creation story in the Book of Genesis is taken as the inviolable, unquestionable, eternal word of God. For these people, the truth about the universe is contained in revered texts, and observations have nothing to do with it. For at least some creationists, it is impossible to imagine any experiment or observation that would convince them to change their minds. For people who think this way, in other words, you do *not* learn about the world by observation, but by consulting the sacred texts.

So with the caveat in mind that not all human societies would agree with the statement, we will begin our discussion of the scientific method with the following:

If you want to learn about the world, you go out and observe it

We will take this to be the first step in the development of modern science and, as we have argued, it was a step taken by many societies in the past. Having said this, however, we have to point out that there are many different kinds of "observation", each appropriate for a different area of science.

When most people think about what scientists do, they think about experiments. An experiment is a specific way of observing nature, usually under highly controlled (and somewhat artificial) circumstances. The basic strategy is to change one thing in a physical system and see how that system changes as a result.

A classic example of this approach to observation can be seen in the Cedar Creek Natural History Area near Minneapolis. There scientists from the University of Minnesota have been studying the way that plant ecosystems respond to changes in their environment. They set up their experiment by having many plots of ground a few yards on a side. Every plot gets the same amount of rain and sunshine, of course, but the scientists can change the amount of other materials on the plots. For example, they can add different amounts of nitrogen to some plots and none to others, then watch the way the different plots evolve over the summer. This is a classic example of a controlled experiment. (For the record, the experiment I've just described showed that adding nitrogen increases the biomass in a plot, but lowers its biodiversity).

In many sciences, this sort of finely controlled experiment can be done, but of others it cannot. An astronomer, for example, cannot build a series of stars to see the effect of adding a particular chemical element to the system, nor can a geologist go back and watch rock layers forming on the early Earth. Scientists in these sorts of fields have to depend more heavily on pure observation rather than experimentation. This doesn't affect the validity of the science, of course, but it's important to keep in mind that knowledge is acquired in a slightly different way.

Finally, as we shall point out in Ch(00), the advent of the digital computer has introduced yet another meaning to the term 'observation'. Over the past couple of decades, as computers have gotten more powerful and our knowledge of the details of physical systems has grown, scientists have started to assemble massive computer programs to describe the behavior of complex systems—everything from the future of the climate to the evolution of ecosystems to the formation of planets. It is becoming more and more common for scientists to 'observe' something like the formation of a planetary system by changing parameters in a computer program, in much the same way as the Minnesota scientists varied the amount of nitrogen in their plots. This sort of 'observation' is usually referred to as 'modeling' or 'simulation'.

Having made these distinctions, it is important to remember that whether scientists start their work with experiments, observations, or simulations, they always begin with a reference to what is seen in the external world.

Regularities

After you observe the world for a while, you come to an important realization: events to not happen at random. In fact, the world we inhabit is surprisingly regular and predictable. The sun always rises in the east and sets in the west, for example, and the days get longer and shorter with the seasons in a predictable way. So predictable is the world, in fact that even ancient civilizations without writing were able to construct massive monuments like Stonehenge to mark the passage of time—a topic to which we'll return in the next chapter. Noticing and stating these regularities is the second important step in the scientific process. We have noted that most civilizations have reached this step in the scientific process. In fact, most of the activities we now characterize as "crafts" actually represent the accumulated experience of generations of people observing the natural world.

It is at the stage of finding regularities that those of us who teach science often begin to encounter a problem, because these regularities are often stated in a strange language—the language of mathematics — rather than in English. Mathematics is a somewhat artificial language that has the enormous advantage of having a high level of precision. Unfortunately, it is also a language that creates a high level of anxiety in many students. Let me say this about mathematics: there is nothing contained in any mathematical equation ever written by a scientist that cannot be stated in ordinary language (albeit not as elegantly). The translation of insights about the world's regularities into mathematics is no more mysterious than the translation of a poem from one language to another. Furthermore, all of the great truths of science can be stated without mathematics, especially since, as we shall see, most of them embody concepts with which we are already familiar from daily life. Consequently, in what follows, with very few exceptions, we will use ordinary language rather that mathematics.

Theories

After we have observed nature long enough to realize that it is regular and predictable, we can move on to what is perhaps the most interesting question in the scientific process. How must the universe be arranged so that it will produce the regularities we actually see? What does our experience, in other words, tell us about the nature of the world we live in? At this point, human thought leaves the realm of immediate experience and begins looking for a deeper meaning to what we see. I will call this process the construction of a theory.

A word of warning: there has been (and continues to be) a great deal of debate among philosophers of science about the precise definition of the word "theory", with different camps placing different constraints on how the world should be used. In addition, there is an unfortunate confusion in the mind of many people because in colloquial language, the word 'theory' is sometimes taken to be synonymous with 'unsupported guess'. You see this occasionally, for example, in the debates about including Creationism on the public school curriculum. Evolution, in these debates, is often derided as 'just a theory'—a statement that emphasizes the difference between the way scientists and the general public use the word.

Because of these problems, let me make a brief aside at this point to make it clear what I (and most scientists) mean when we talk about a theory. I have to start this discussion with a somewhat unusual observation: as good as scientists are at learning about how the universe works, they are really pretty bad at naming the things they discover. In the next section, for example, we will see that the cornerstone—the absolute bedrock—of science is a relentless testing of ideas against observation. It would be very nice, then, if an idea being proposed for the first time were called an 'hypothesis', and after it had been verified a thousand times it became a ’theory’, and, finally, after a million verifications it became a ‘law’. Unfortunately, it just doesn’t work that way. Whatever name an idea gets when it is first introduced stays with it, no matter how well it is supported by observation subsequently.

Let me give you an example: In Ch(00) we will talk about the work of Isaac Newton and, in particular, his development of what was called the ‘Law’ of Universal Gravitation. For several centuries this was our best explanation of the phenomenon of gravitation, and it is still used today when we want to send a space probe to a distant planet. In the early twentieth century, Albert Einstein developed a deeper explanation of gravity, which goes by the name of the ‘Theory’ of General Relativity. This ‘Theory’ contains within it, as a special case, Newton’s ‘Law’ of universal gravitation. Thus in this example the thing we call a ‘Law’ is actually less general and less well validated than the thing we call a ‘theory’. This is a dramatic example of the kind of deficiency in the scientific naming process I mentioned above, but far from the only one.

Because physics was the first of the sciences to develop in its modern form, there has been a tendency for subsequent scholars to try to cast their science in the mold first established by physicists. There is even a tongue-in-cheek term—“physics envy”—that academics use to describe this phenomenon. But just as there are different types of ‘observation’ appropriate to different branches of science, so too are there different types of theories.

Physics tends to be an exact science, driven by precision experiments and highly quantitative theories. In the best cases, in fact, the results of theoretical calculations and laboratory experiments can agree to more than ten decimal places! The theories of physics, as we shall see in Ch(00), tend to be stated in rigorous mathematical terms (although, as stressed above, they *can* be stated in words as well). This gives them an aura of precision that can sometimes be deceiving, but which characterizes one type of ideal for a scientific theory.

At the other end of the spectrum are theories that are less quantitative, theories that describe general trends and processes. One example of this type of theory is Darwin’s original statement of the laws of natural selection, which we will discuss in Ch (00). Rather than making precise predictions (“42.73 percent of this type of animal will survive long enough to have offspring”), this theory enunciates general rules about how populations develop over time (“In this situation, animal A is more likely to have offspring than animal B”). Many theories in the historical sciences, such as the theory of plate tectonics (our modern view of the Earth’s structure) are of this type. (Having said this, I have to point out that since Darwin, many highly quantitative developments have been added to the theory of evolution. It is not at all unusual, for example, to hear a modern paleontologist using DNA analysis or complex mathematical calculations to buttress a thesis about the development of a particular organism.)

This difference between the different kinds of theories in the sciences actually fuels one of the more interesting debates among scholars today. The debate centers on the question of whether the universe is deterministic or contingent. As we shall see in Ch (00), the work of Isaac Newton led to a particularly mechanical view of the universe, one in which observed phenomena were thought of as being analogous to the hands of a clock. In this picture, the gears of the clock are the laws of nature, and if we only knew enough about the gears we could predict exactly where the hands would be at any time in the future. The universe, in this picture, is completely deterministic. On the other side, people like the paleontologist Steven Jay Gould have argued that the universe (at least in its biological aspects) is contingent—"Run the tape again" he argued, "and you get a completely different tune."

This is one of those deep question that it's easy to ask and very difficult to answer. For the record, my own conclusion that that the universe is a lot less contingent than Gould would have it, and probably a little less deterministic than Newton thought.

Prediction and Verification

Once we have an idea about how the universe works, we are ready to take the final step in the scientific process—a step, I argue, that separates science from all other human intellectual activities. The basic idea is that we look at our theory and ask a simple question: does this theory predict anything that I haven't seen yet? If the theory is worth anything, it will suggest many such observations of as yet unobserved phenomena, and this, in turn, leads to new experiments and observations. In fact, it is this relentless testing of theories against actual observations of the natural world that is the distinguishing mark of the scientific enterprise. To put it bluntly,
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In science there are right answers, and we know how to get them.

There are several points that can be made about this statement. We started the scientific process by observing nature and, in the end, we finish it in the same way. Science begins and ends by comparing our ideas against the realities of the natural world, by observing natural phenomena. It is the presence of this impartial outside arbiter of ideas that makes science different from other fields. Every scientist (the author included) has had the experience of starting an argument with reasonable hypotheses, following impeccable logic to an unquestionable conclusion, only to have experiment show that the whole thing to be wrong. In the end, it doesn't matter how well you frame your arguments or how much status you have in the scientific community—if the data doesn't back you up, you are wrong. Period.

Once we realize how important this verification process is, however, we have to recognize that it can have two possible outcomes. It may be that our predictions are borne out by observation. Oddly enough, this is not the outcome most scientists hope for when they begin an experiment, because such a result really doesn't add much to our store of knowledge. Furthermore, in the scientific community there is normally much more of a cachet attached to disproving a theory than affirming it. Nevertheless, a positive outcome means that our theory has been confirmed. In this case, scientists will usually look for another prediction that they can test.

The other alternative to the verification process is that the prediction may not be borne out. What happens in this case depends on the status of the theory being tested. If it is a new theory, being tested for the first time, scientists may simply conclude that they have gone down a blind alley, abandon the theory, and try to construct a new one. If, on the other hand, the theory has enjoyed some success in the past, scientists will look for ways to modify and extend it to accommodate the new finding. Instead of asking "What other theory can we build?", in other words, they will ask "How can we modify this theory to make it more complete?" We will see many examples of both of these processes as we examine the historical development of science.

Just so that we have a concrete example of the prediction-and-verification process in mind, let's turn our attention to a series of events that followed Newton's development of his mechanistic view of the universe. In one fell swoop, he had reduced millennia of astronomical observations to simple consequences of a few deep physical laws. In his orderly, clockwork universe there was only one flaw—the occasional appearance of comets.

Think for a moment about how a comet must have appeared to people like Newton. The orderly progression of the planets through the sky—motion we compared to the movement of clock hands above—is suddenly interrupted by the appearance of a strange light in the sky. The comet hangs around for a while, then disappears. What was that all about?

Edmond Halley was a distinguished scientist who settled down as Astronomer Royal after an adventurous youth. A friend of Newton, he decided to tackle the comet problem. According to one story, he was having dinner with Newton and asked his friend a simple question: if comets were material bodies affected by gravity like everything else, what shape would their orbits be? Newton had thought about this problem, and told his friend that comets would have to move in an ellipse. Armed with this knowledge, Halley examined data on 26 historical comets to determine their orbits, and discovered that three of those comets moved in exactly the same elliptical path.

Flash of insight. That wasn't three separate comets in the same orbit—it was one comet coming back three times. Using Newton's Laws, Halley calculated when the comet would be seen again and made his prediction—it would return in 1758. Sure enough, on Christmas Eve, 1758, and amateur astronomer in Germany turned his telescope to the sky and saw the comet. As we shall argue in Ch(00), this event, which historians call the 'recovery' of Halley's comet, can be taken to be symbolic of the development of the modern scientific method.

I would like to make a couple of points before we leave Halley. In the first place, we can imagine a scenario in which the comet failed to appear—things didn't turn out that way, but they could have. This means that Halley's prediction could have been wrong. In the language of philosophers, the Newtonian theory is 'falsifiable'. (In the American legal system, this same property of scientific ideas is called 'testability'). It is important to realize that a falsifiable statement can be either true or false. For example, the statement “The Earth is flat” is a perfectly falsifiable scientific claim that happens to be false. The statement “The Earth is round” is also falsifiable, but happens to be true. All real scientific theories must be falsifiable (which is not the same as saying they must be false). If you have a theory that cannot possibly be proved wrong, as is the case in some versions of Creationism, it simply is not science.

I can’t leave Halley, though, without quoting a statement he made when he predicted the return of his comet

> *Wherefore, if (the come)t should return again about 1758, candid posterity cannot refuse to acknowledge that it was first discovered by an Englishman.*

The Growth of Science

Most of the time, most scientists are engaged in pursuing their craft in more or less the order given above, beginning and ending their work with observations of nature. As I intimated above, however, these steps are not a cookbook, and there are times when scientists joyfully ‘break the rules’. Perhaps the most famous example is Albert Einstein’s development of the Theory of Relativity, which began not with observation, but with a deep analysis of a fundamental contradiction between two different areas of physics. Once enunciated, though, the theory had to go through the same prediction-and-verification process as everything else. (We’ll talk about relativity is more detail in Ch(00)).

Just as there are different types of ‘observation’ appropriate to different areas of science, there are different ways that areas of science advance. One way that science can change is by the simple replacement of one theory by another. When Nicolas Copernicus first put forward the idea that the Earth orbited the sun rather than standing stationary at the center of the universe, his ideas eventually replaced the prevailing theories about geocentrism. Generally speaking, this kind of replacement process tends to occur early on in the development of a science, while there are still a lot of unknowns and a lot of room for theorists to maneuver. The last time this sort of wholesale replacement happened was in the Earth sciences in the 1960’s, when the modern theory of plate tectonics, with its mobile continents, replaced the old theories of the fixed Earth.

Once a field of science reaches a certain level of maturity, however, a different type of change starts to predominate. Instead of replacing old theories with new ones, scientists extend existing theories, adding new material without abandoning the old. As we shall see in Ch(00), the great advances in physics in the twentieth century (relativity and quantum mechanics) do not replace Newtonian physics, but extend it to new areas, areas where it was not originally known to apply. We shall see that if we apply the rules of quantum mechanics, derived for the world of the atom, to large scale objects, those rules become identical to Newton’s Laws. Thus this type of change in the sciences can be thought of as being analogous to the growth of a tree. New material is always being added on the periphery, but the heartwood remains unchanged.

Another way of thinking about this picture of incremental growth in the sciences to go back to our basic premise that science begins and ends with observation. Every great law of science is based on observation, and is only as good as the observations that back it up. Newton's picture of the universe is massively supported by observations of normal sized objects moving at normal speeds, but until the twentieth century we had no observations of objects on the scale of atoms. When those observations came in, they led to a new field of science—quantum mechanics—but did not contradict the old constellation of observations. Thus, Newton's Laws remain the heartwood, and we still use them to build bridges and airplanes, even though we understand that they can't be applied outside of their original area of validity.

And this brings us to another important aspect of the scientific process. The pragmatic methods I've described can be thought of as a way of finding progressively more exact approximations to the truth, but they will never get us to Truth. Every law of science, no matter how venerable, can, in principle, be proved wrong by a new observation. Such a turn of events is surely very unlikely, but the requirement of falsifiability demands that it be possible. It is the nature of science that all truths are tentative, subject to the results of future observations.

Finally, I would like to end this introduction to the scientific process by discussing an aspect that has been the subject of academic debate in recent years. This debate has to do with the role of social norms in the development of scientific theories. On the one side we have working scientists who believe that they are finding better and better approximations to reality through their work. On the other side are philosophers and sociologists of science, who argue that scientific theories are, in fact, the result of what they call social construction. In its most extreme form, this argument becomes a kind of solipsistic exercise—in essence, the argument that an observed regularity in nature has no more intrinsic meaning than the convention that a red light means 'stop' and a green light means 'go'.

It shouldn't surprise you that working scientists , with their emphasis on the observation and verification, who heard about these arguments disagreed violently. This led to an episode called the 'Science Wars', which was basically a debate between the views outlined above. (I should say, however, that most scientists never heard of this debate, which made many observers wonder if you can really have a 'war' when one side isn't aware that it's going on).

The basic issue in the 'Science Wars' was the extent to which social structures affect the results that scientists derive. That society affects science (and that science affects society) can scarcely be denied. The real issue is the extent to which social effects can determine the results of the scientific process outlined above.

There can be little dispute that in the short term, social influences can have a large effect on scientific development. Governments, for example, can encourage certain areas of research by funding them, and discourage others—even make them illegal (as has been done for human cloning in many countries, for example). In rare instances, governments can even try to suppress scientific results. (If you want to see a particularly egregious of this, Google 'Trofim Lysenko' to learn how Josef Stalin delayed the development of modern biotechnology in the old Soviet Union by several generations). In addition, there are fads and trends in the sciences themselves that can influence the way research is done and the way it is interpreted.

In the long run, however, these kinds of effects are ephemeral. As we emphasized above, in the end what matters in science is verification through observation. No amount of government intervention or social pressure could have removed Halley's comet from the sky on that day in 1758, for example. Even cases of scientifimistakes (which happen) and scientific fraud (which also happens, though less frequently) are eventually uncovered by the scientific process.

There is only one place where social influences can have an important effect in the scientific process, and that is in the construction of theories. Scientists, after all, are members of their societies. At any given time, in any given society, there are some ideas that simply can't be thought, not because they are forbidden, but because they are just outside of the mental landscape of the time. For example, Isaac Newton could no more have conceived of the theory of relativity than he could have written rap music. In this sense, and in this sense only, we can speak of science as being 'socially constructed'.

In any case, the process outlined above represents the way that science works in its mature form. In what follows we will see how the elements of the scientific process developed in cultures around the world, reaching its modern form in western Europe in the 1600s. From there, we will trace its spread, first to places like Russia and America on the periphery of Europe, and then to the entire globe. fc