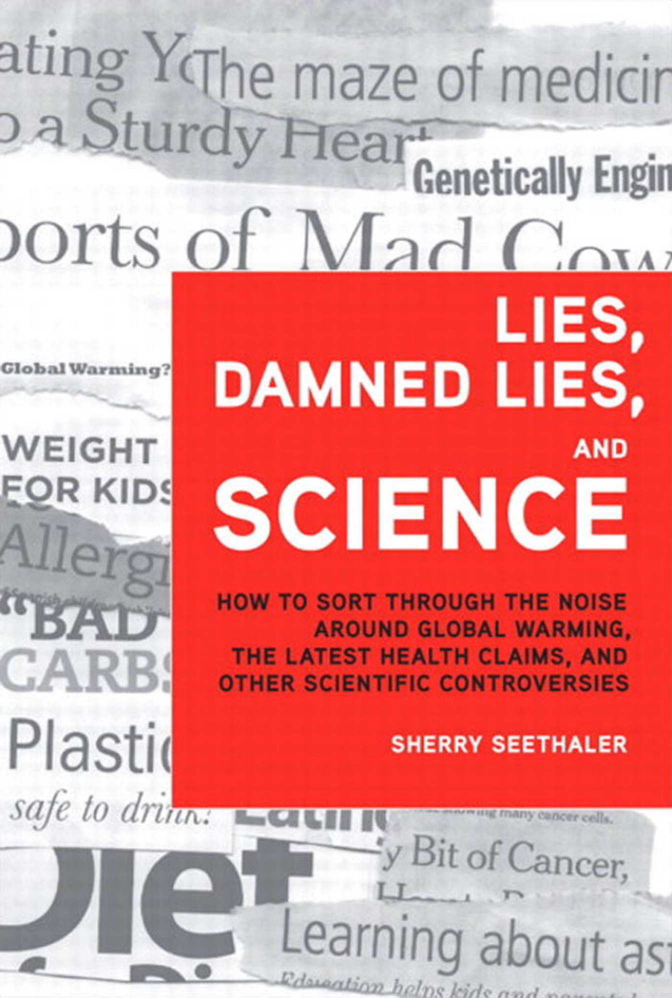

LIES, DAMNED LIES, AND SCIENCE

HOW TO SORT THROUGH THE NOISE AROUND GLOBAL WARMING, THE LATEST HEALTH CLAIMS, AND OTHER SCIENTIFIC CONTROVERSIES

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Preface

Be very, very careful what you put into that head, because you will never, ever get it out.

—Thomas Cardinal Wolsey (1471-1530)

My goal in writing this book is to help people make sense of the science-related issues that impact their daily lives. *Lies, Damned Lies, and Science* provides an enlightening approach for contemplating scientific issues, and brings these issues into focus the way new glasses sharpen one's vision. In other words, the book is a new lens through which to view the world. Each chapter reveals a unique set of elements that need to be taken into consideration when reasoning about a complex science-related issue. In addition to bringing these elements into focus, the book shows how they fit together into something greater than a sum of parts.

Most of the messages that bombard us everyday are carefully selected to present just one of a kaleidoscope of possible perspectives on technological, environmental, economic, and health issues such as global warming, mad cow disease, nanotechnology, genetically engineered food, who should take cholesterol-lowering drugs, and what are the merits of banning plastic bags. Oversimplified black-and-white perspectives of issues come from those who have a vested interest in convincing others of their point of view, or who are simply relaying information without thinking critically about it. This book explores ways to achieve more nuanced and balanced perspectives on a wide range of issues.

In a society in which science and technology drive the economy and infiltrate every aspect of daily life, it is dangerous for an elite few to make the decisions about how technology is used, who will be given access to it, and how money is spent to research scientific solutions to societal problems. Ironically, those with the power to make these decisions rarely have any background in science. Therefore, they are especially vulnerable to being hoodwinked by those who hold stake in an issue and have the money to get their voices heard. Yet, we too can make our voices heard through sound, evidence-based political, consumer, and medical decisions. To do this, we need to be armed with the knowledge that makes it difficult for clever stakeholders to deceive us.

Too many people lost confidence in their ability to understand science because they did poorly in science class in high school. However, even folks who excelled in high school science classes and majored in a scientific discipline in college are rarely adequately prepared to think critically about the science they encounter in their daily lives. High school and even college science tends to be focused on facts, formulae, and experiments with known outcomes. In the real world, there is much more uncertainty and interpretation. Decisions about contemporary scientific issues often must be made on the basis of incomplete information, and conflicting viewpoints are the norm rather than the exception. This book unravels the complexity of such issues to help scientists and nonscientists alike identify hogwash and balance tradeoffs to make well-reasoned decisions about science in everyday life.

Introduction

Knowledge is power.

—Sir Francis Bacon (1561-1626)

If the words "xylem" and "phloem" bring to mind musical instruments rather than plants, and you could not tell a gastropod from an annelid if one turned up in your breakfast cereal, you are still perfectly capable of learning to see through the hype and hogwash that come your way. This book will give you something more powerful than facts. It will give you tools—the kind of tools that no one (not even the self-proclaimed science nerd) learned in school. The power of these tools is that they can be applied to any issue that arises. New facts will come to light over time, and old ones will be overturned, but these tools will last you a lifetime. They will help you interpret information that comes your way, and they will make it possible to pinpoint the relevant information that is missing from the discussion.

Science is omnipresent. We are surrounded by the fruits of the labors of scientists and engineers—from computers and cell phones to genetically engineered food to sportswear made from new types of fabric. Labels on snacks inform us that they are "all natural" or "reduced fat." Television commercials tell us to ask our doctor about medicines that can make us happier, more carefree, and full of energy. Headlines warn about the emergence and spread of new diseases. Our politicians hotly debate issues such as the regulation of stem cell research and what to do about global warming.

Consequently, science is central to an increasing number of the decisions we make each day. But while science is prevalent, the science-related information that comes to us is piecemeal and disconnected, often misleading, and sometimes dead wrong. To make matters worse, the textbook science we learn in school leaves us unprepared for grappling with complex contemporary scientific issues. Making science-related decisions in our daily lives requires more than the scientific "facts" we had to memorize and recall on tests. Sound decisions require the careful weighing of the pros and cons—tradeoffs—of each possible choice.

Every decision has tradeoffs. For this reason, we must be willing to challenge our politicians, lobbyists, marketers of consumer goods, proponents of the latest diet craze, and even our doctors. We should demand more balanced assessments of the impact of new legislation, the risks and benefits of new technologies, and the side effects of treatments for ailments. Unfortunately, our willingness to accept simple answers can make it easy for advertisers to pull the wool over our eyes, and make us deaf to the voices of dissenters when a clever-talking politician makes an action sound sensible and foolproof.

Lies, Damned Lies, and Science will empower people of all ages and educational backgrounds to think critically about science-related issues and make well-balanced decisions about them.

Those who promote incorrect information, either because they are trying to manipulate you, or because they themselves have been duped or are simply misinformed, rarely have more knowledge about science than you do. What they have are skills at using information to suit their purposes. Your strongest line of defense against them is the set of tools you will learn in this book. After reading *Lies, Damned Lies, and Science*, you will have a solid grasp of how scientific knowledge develops, a familiarity with the kinds of individuals and groups filtering the scientific information that comes your way, and an understanding of the multitude of ways in which they can hoodwink you. As you read each chapter, you will become increasingly impervious to the efforts of others to manipulate you with misinformation.

Each of the ten chapters in the book describes one tool and illustrates it through thought-provoking topics in health, the environment, and technology, including the genetic engineering of crops, mad cow disease, global warming, electromagnetic fields, and drug treatments for depression. Every chapter will take you one step closer to being a savvy scientific reasoner. The chapters reveal how to

1. Understand how science progresses and why scientists sometimes disagree.
2. Identify those who hold stake in an issue and what their positions are.
3. Elucidate all the pros and cons of a decision.
4. Place alternatives in an appropriate context to evaluate tradeoffs.

5. Distinguish between cause and coincidence.
6. Recognize how broadly the conclusions from a study may be applied.
7. See through the number jumble.
8. Discern the relationships between science and policy.
9. Get past the ploys designed to simply bypass logic.
10. Know how to seek information to gain a balanced perspective.

Chapter 1, "Potions, Plot, Personalities." Everyone who has done science experiments in high school or as a freshman in college knows that there is only one correct outcome for an experiment, so why would scientists disagree about scientific findings? Sadly, school science usually presents an unrealistic view of how science really progresses. It gives the impression that doing science is about completing a set of steps, akin to following a recipe. This perspective fails to help us reason about current issues in science—science in the making. Without understanding why there could be legitimate reasons for scientists to come to different conclusions, it is frustrating to hear that scientists disagree, or that they have changed their minds about science-based advice they gave in the past. By understanding how science works, especially the role of interactions among scientists in the progress of science, it becomes easier to understand why scientists have disputes, to make sense of what is actually being disputed, and to recognize when the media is deliberately hyping disputes between scientists for drama, or missing the dispute entirely.

Chapter 2, "Who's Who?" Environmentalists. Farmers. Stockholders. Starving people in the poorest nations. Politicians. Consumers. Scientists. Corporations. These are all groups that have something to gain or to lose from new technologies, new legislation, the funding of various types of research, or the oversight of certain industries. Identifying the different groups can provide order to the cacophony of stakeholders' voices. Also, some voices may be missing from the mix; individuals with the fewest resources are often unrepresented. Knowing who the possible stakeholders are for a particular scientific issue, and seeking out the positions and opinions of those who tend to be less successful at making themselves heard, is essential for coming to balanced decisions.

Chapter 3, "Decisions, Decisions." Stakeholders represent their positions in the best possible light by focusing on the positive and omitting mention of the possible negative consequences. Of course, a balanced decision is one that is made by sorting through all relevant options and assessing the pros and cons of each. Otherwise, if alternatives and possible consequences are omitted from consideration, a decision is essentially being made at random. It is not much more informed than drawing choices from a hat. Since stakeholders cannot be depended on to present the whole picture, it is essential to be familiar with the themes of tradeoffs that arise in decisions about science-related issues. Using knowledge about these themes of tradeoffs, you will be able to ask the right questions to get the full set of alternatives and possible outcomes to make an informed choice.

Chapter 4, "Compare and Contrast." Ideas can be misleading when they are taken out of the big picture context, or when something is evaluated without reference to its alternatives. Imagine someone said that he is from a place where a loaf of bread costs a nickel. To make that information meaningful, most people would automatically ask about the typical earnings of an individual from that place. However, too often when we receive information, we fail to ask, "compared to what?" For example, if the news tells us that a new surgical method has led to 3,000 deaths, we jump to the conclusion that the surgical method is dangerous. But dangerous relative to what? Does not having surgery to correct the illness lead to more deaths? What treatment was used previously, and how did patients fare with it? Considering issues in an appropriate context will help you accurately evaluate the pros and cons of a decision.

Chapter 5, "What Happens If...?" What is compelling proof that a nutritional supplement can boost the immune system, that human activities are changing global climate, or that a new technology is not deleterious to human health? Many claims are about a factor causing some result. The evidence offered in support of these claims ranges from the testimonials that bombard us everyday, "Product X changed my life," to the controlled scientific experiment. Despite what the plethora of claims may lead one to believe, it is difficult to prove that two things are linked by cause rather than coincidence. Delving into the strengths and weaknesses of the different types of evidence reveals when it is and is not possible to conclude that there is a causal link between two occurrences.

Chapter 6, "Specific or General." Data collected under one set of circumstances are often used to draw conclusions about different circumstances. For example, conclusions may be drawn about the danger of a chemical to human health based on toxicity tests in animals. However, data collected with one population, in a specific location, under certain conditions, or at a particular epoch cannot necessarily be legitimately applied to other situations. Because stakeholders often apply conclusions much more widely than they should, it is critical to understand what kinds of problems can arise when findings are applied to novel situations.

Chapter 7, "Fun Figures." Many stakeholders will attempt to blind you with statistics. Used correctly, statistics can be informative, but more often than not, the numbers are inadvertently misleading or are deliberately being used to tell lies. Evaluating the statistics presented by stakeholders does not require sophisticated math skills. Instead, it is a matter of identifying the common pitfalls that arise when interpreting what the numbers mean, such as confounding factors, lack of significance, meaninglessness, and oddities in the way the data were collected.

Chapter 8, "Society's Say." Science is embedded in a greater social fabric. Society puts limitations on the kinds of experiments that can be performed by prohibiting experiments deemed unethical. The availability or lack or funding for certain types of research projects also impacts science. For example, following the attacks of September 11, 2001, and the anthrax mailings, scientists whose research had applications to the war on terrorism found it easier to get research funds. Science and society intersect in another way when questions arise about scientific issues that cannot be answered by science itself. These ethical and moral questions come into play when individuals and governments make decisions about scientific issues. Ethical and moral questions are not constrained to traditionally sensitive issues such as the use of stem cells from human embryos. Ethical concerns, including how much risk is acceptable and how taxpayer dollars should be spent, arise in debates about issues like the use of pesticides, nuclear power, space exploration, and how to tackle diseases that plague developing nations. To judge the soundness of new policies, it is important to understand what values were applied to develop them.

Chapter 9, "All the Tricks in the Book." We all want to believe that our brains sort through information in the most rational way possible. On the contrary, countless studies by psychologists, educators, and neurobiologists show that there are many foibles of human reasoning. Common weaknesses in reasoning exist across people of all ages and educational backgrounds. For example, confirmation bias is ubiquitous. People pay attention to information that supports their viewpoints, while ignoring evidence to the contrary. Confirmation bias is not the same as being stubborn, and is not constrained to issues about which people have strong opinions. Instead, it acts at a subconscious level to control the way we gather and filter information. Most of us are not aware of these types of flaws in our reasoning processes, but professionals who work to convince us of certain viewpoints study the research on human decision making to determine how to exploit our weaknesses to make us more susceptible to their messages. Becoming more aware of our own vulnerabilities stymies their efforts.

Chapter 10, "Fitting the Pieces Together." Making sense of an issue requires knowing when to ask questions, what questions to ask, and whom to ask. It is critical to take stock of the information presented, and determine what information is missing. For complex issues, information gathering is akin to peeling an onion; successive levels of understanding reveal themselves as one digs deeper for information. With practice, it becomes natural to move between these levels of understanding when reasoning about an issue. In doing so, what was once an impenetrable mass will reveal its various components. Building on the tools introduced in Chapters 1 through 9, Chapter 10 discusses the different levels of understanding that play a part in making sense of science-related issues. It also provides details about where to find information and the reliability of different sources of information.

Conclusion, "Twenty Essential Applications of the Tools." In this Information Age, lack of information is rarely a problem. Instead, the challenge is sifting through and making sense of mounds of information. The tools discussed in Chapters 1 through 10 facilitate the sorting and synthesis of information by focusing attention where it is needed most. They provide a framework that can organize what seems like hopeless complexity into a comprehensible set of ideas, useful for making decisions and integrating new ideas as they come along. The Conclusion lays out the ideas discussed in *Lies, Damned Lies, and Science* in a handy, easily referenced format that will facilitate sense making about new issues as they emerge.

1

Potions, plot, personalities: understand how science progresses and why scientists sometimes disagree

In the sixth Harry Potter book, *Harry Potter and the Half-Blood Prince*, Harry developed a flair for making potions by following instructions handwritten in the margins of his potions textbook by the book's previous owner. To make a Draught of Living Death, for instance, the handwritten notes in Harry's book advised him to stir his potion clockwise after seven stirs in the opposite direction. The tiny tweak in the procedure helped Harry achieve potion perfection. Meanwhile, Harry's brilliant friend, Hermione, who carefully followed the original textbook instructions line by line, became frustrated when she could not get her potions to turn out properly. Of course, at Hogwarts School of Witchcraft and Wizardry, potion making relies on magic. Surely, in a university laboratory outside J. K. Rowling's magical world, the synthesis of chemicals would not be affected by something as insignificant as how the chemicals are stirred? Surprisingly, when a published chemical reaction—the cleaving of bonds between carbon atoms—inexplicably stopped working, a frustrating eight-month investigation did indeed trace the problem to how the solution was stirred. Iron was leaching out of the well-used magnetic stir bar of the chemist who developed and published the chemical reaction. It turned out that the metal was important for catalyzing the reaction. Researchers attempting to replicate the reaction had unwittingly removed the catalyst because they were using a new stir bar with its metal core well sealed in its plastic casing. There was no need to invoke the supernatural to explain the mystery of the failed reaction—the findings were published in the sedate chemistry journal

Organometallics—but this example shows that science, like *Harry Potter*, has a plot with unexpected twists and turns. Because the science that comes to us in our daily lives is usually science-in-the-making, to make sense of it, it is essential to understand how science really progresses.

Brewing chemicals in a laboratory is a stereotype that comes to mind when we hear the word "scientist," but scientists actually engage in a wide range of activities. Many scientists—for example, ecologists, archeologists, climatologists, and geologists—spend much of their time doing field research. This may involve documenting the behavior of animals in the wild to understand population declines, collecting ice cores in Antarctica and using gas bubbles trapped within them to gain information about changes in the earth's atmosphere over time, or recording seismic activity near volcanoes or fault lines.

Of course, scientists often do spend considerable time in a laboratory, but the work they do there differs depending on several factors. Some of these include: whether the laboratories are affiliated with universities, hospitals, companies, zoos, or the government; how many scientists work there; how much funding they have; what kinds of research questions they focus on; what kind of equipment is used; and even where the labs are located. For example, physicists who study neutrinos—one of the fundamental particles that make up the universe—use special laboratory facilities a mile or more beneath the earth's surface.

It should come as no surprise, then, that despite what most science textbooks may lead you to believe, there is no single method of doing science. This is one of three aspects of science frequently misrepresented by precollege and even college science courses. The second problem with these courses is that they leave the learner with the impression that science is merely an accretion of new ideas. However, in reality, controversy and revolutions in scientific thought are common features of science. Third, despite stereotypes of scientists as loners, interactions between scientists play many important roles in the progress of science. This chapter dispels the myths about these aspects of scientific progress and reveals how dispelling each myth can make one a more critical consumer of the claims about science that come through the media and other sources.

"The scientific method"—not as easy as pi

Introductory science textbooks often lay out a neat set of steps they refer to as "the scientific method" and leave readers with the impression that this is all they need to know about how science is done. The steps most texts describe can be summarized more or less as follows:

1. Develop a hypothesis.
2. Design an experiment to test the hypothesis.
3. Perform the experiment and collect data.
4. Analyze the data collected.
5. Decide if the data support or refute the hypothesis.

This view of science is oversimplified, incomplete, and sets people up for failure when they try to make sense of science in the real world. While it might be reasonable to give children a simplified view of science to begin with, the problem is that many people, even college students who major in science, never get to see what authentic science is like. With some notable exceptions, undergraduate science laboratories are cookbook exercises, and undergraduate lecture courses are just that—lectures, usually more about presenting facts to be memorized than discussing how those facts came to be. For those who go on to graduate school in the sciences, it is often a shock when it takes months to figure out why experiments are not working, that what initially seemed to be an exciting result is an error, or (for the lucky ones) that what seemed to be an error turns out to be an exciting result.

The process of testing hypotheses is not nearly as cut-and-dried as the textbook scientific method would lead one to believe. First, multiple hypotheses are possible, but the one that ultimately stands up to the test may not be apparent from the start. It may only be proposed after several other hypotheses have been eliminated. Second, there may be more than one type of experiment that can be done to test a hypothesis, and each possible experimental test will have its own set of pros and cons. These include time and cost required, expected accuracy of the results, feasibility of applying the results to other situations, ease of acquiring the necessary equipment, and amount of training needed to use that equipment. Then again, the tools or techniques required to rigorously test the hypothesis may not exist. For example, geologists cannot physically probe the center of the earth. Instead they must make inferences about it based on seismic data. Third, data analysis is rarely simple and straightforward. Decisions must be made about whether to include data that appear spurious, what to do if experimental subjects dropped out of an experiment before it was over, and, as discussed in the next section, how to interpret data that was collected using new technologies. Finally, it may be possible to draw more than one conclusion from the same data. For example, if multiple factors can each play a role in causing something, it will likely take more than one experiment to tease them apart. A discussion of these caveats of designing experiments and interpreting data is usually absent from media reports about science.

With new tools, researchers can answer new questions—but only after the bugs are worked out

Over time, as new technologies develop, scientists can begin to test hypotheses they could not have tested in the past. But for the conclusions drawn from experiments using new procedures or new technologies to be accepted by the scientific community, other scientists must agree that the new technique does measure the effect of interest, and that what is being "observed" is real.

For example, chemists often want to know the structure of particular molecules. This information is used in many ways, including drug design. One way to determine a molecule's structure is Nuclear Magnetic Resonance (NMR). NMR relies on the fact that when a molecule is placed in a magnetic field and probed using radio waves, the behavior of the nucleus of each atom depends on the identity of its neighboring atoms. A chemist can load a vial containing a sample of the molecules of interest into an NMR machine and get a graph that consists of a series of peaks. The structure of the molecule is inferred from this graph. The key word is "inferred." The chemist operates on the assumption that the peaks correspond to atoms, and are not some artifact of the procedure like electrical surges or vibrations in the room.

NMR is a well-accepted experimental technique used everyday by scientists all over the world. For a technique like NMR to become accepted, it must withstand a series of tests. For instance, if an older technique measures the same thing (presumably less efficiently), then the output of the new technique can be compared to that of the old. Alternatively, researchers can study the output of the new technique when it is used to analyze a set of known standards. For a new NMR technique, scientists could take chemicals that have a known molecular structure, run NMRs, and have other scientists, who did not know what the original samples were, interpret the graphs. If this can be done accurately and consistently over a wide range of samples, the technique can be used to identify unknown samples.

Even when the procedure or technology has been used for a time in one context, or to collect one type of data, applying it to collect another type of data, or to collect data under different conditions, may lead to disputes about what is really being observed. For example, a test that measures the concentration of a specific chemical may work well when the solution being tested is simple. On the other hand, when many other chemicals are present, they may participate in side reactions that interfere with the analysis. So the test may give accurate readings for well water or lake water, but may give false readings when applied to the analysis of blood samples or industrial waste. For this reason, new applications of procedures require careful consideration and verification.

Furthermore, although scientists may agree with each other on what they are observing with a given procedure, they may not agree on what the observations mean. For example, some brain scans allow scientists to measure blood flow to different regions of the brain. By studying changes in blood flow when people engage in different tasks—such as solving jigsaw puzzles, listening to music, memorizing a list of words—scientists infer what regions of the brain are necessary for those tasks. But an increase in blood flow does not necessarily mean that region of the brain is "thinking." Other scientists could accept that the scan is indeed measuring blood flow, while arguing that the increase in blood flow means that more messages are being sent through that region of the brain, rather than being processed there, or that the blood flow is due to an increase in cell maintenance and repair that occurs after a region of the brain has finished thinking. They might suggest further tests of the technique to address their concerns.

Uncertainty about what tool or procedure to use, and the risk that results are not what they appear to be, are problems common to all the scientific disciplines. The development of new tools allows scientists to answer questions they could not answer in the past, and the answers to those questions will lead to new questions, and so on. Therefore, new technologies and procedures are crucial to the progress of science. At the same time, other scientists unfamiliar with a new tool may express skepticism and call for others to replicate the experiments. Because this skepticism often comes to us in the form of sound bites, and because uncertainty about experimental tools is an aspect of science that is not familiar to most people, even people with a bachelor's degree in science, the skepticism may seem like waffling. Waffling is annoying when you are trying to make decisions on the basis of the scientific information that comes your way. However, if a new technique is the source of the uncertainty, time and future experiments will confirm or disconfirm its usefulness and clear up uncertainty.

Myth #1

Science is a step-by-step process in which scientists develop a hypothesis, design an experiment to test it, perform the experiment, collect data, analyze the data, and accept or refute the hypothesis based on it.

Not exactly. If science really were so straightforward, hypotheses would not remain untested for long periods of time. Scientists would not disagree about results.

Implications for making sense of scientific issues:

A basic understanding of the challenges scientists face in testing hypotheses takes the mystery out of why hypotheses remain untested and why scientists disagree. For example, new experimental techniques make it possible to test hypotheses that could not be tested in the past. At the same time, new experimental techniques must hold up to scrutiny before the scientific community will accept the results collected using them. Discord about an experimental technique should not be treated as the sign of an impasse. Instead, the results should be taken into consideration, but decisions based on the results collected using the technique should be conservative until the technique has been rigorously tested.

Models play a critical role in the progress of science

Volcanoes are a real hit with kids. Build a hollow, cone-shaped structure from some simple household items, throw in some vinegar, red food dye, and baking soda, and whoosh—the eruption makes a big, foaming mess.

Of course, while these science fair model volcanoes bear a superficial resemblance to real volcanoes, they function in a completely different way. Obviously, scientists looking for a system on which to conduct laboratory tests to better understand volcanic eruptions would not turn to the popular science fair volcano. This highlights a critical feature that distinguishes the kinds of models that were used to teach us science and the kinds of models that scientists use to understand the world. On the one hand, teachers and parents use model volcanoes to create excitement and give young students a physical object to which they can tie the earth science concepts they are learning. Likewise, a teacher may use ping pong balls to show how molecules of a gas bounce off each other and the sides of a container. For the purpose of helping students understand difficult scientific concepts, it does not matter that real magma behaves very differently than baking soda and vinegar, or that ping pong balls do not really mimic the behavior of gas molecules. These models make science more visual and are practical teaching tools. On the other hand, if the goal is to use a model to test hypotheses about how things work in the real world, the features of an ideal model are very different. In that case, the model does not have to look like its real world counterpart; it just has to act like it. For example, to understand what is happening in a cell when it switches between different types of fuel (carbohydrate, fat, protein), a plastic model of the cell showing all of the cell's organelles is completely inadequate. Considerably more useful is a computer program that simulates all of the major processes and chemical reactions in the cell.

Scientists use many different types of models, but in recent decades as computers have become increasingly powerful, computer simulations have become essential tools for scientists studying all kinds of complex systems. For example, computational models are used to understand the biological processes occurring within organisms, the functioning of ecosystems of organisms, the evolution of the universe, and climate changes. One kind of computer simulation is like the simulations used to make special effects in movies and computer games in that it aims to create a visual representation of reality (or unreality, in the case of some games and movies). Scientists use these kinds of simulations, for example, to determine the three-dimensional structure of proteins that play a role in different diseases. Knowing the structure of a protein makes it feasible to design a drug that can bind to the protein and modify its function. The second type of computer simulation is considerably more abstract and mathematical. Its output may not visually represent reality at all. Instead, it is used to determine what may occur given a specific set of initial conditions. Will the death of a star of a certain size give rise to a black hole? Given certain patterns of use of a new antibiotic, how long will it take before bacteria that are resistant to that antibiotic become widespread? How many degrees will global temperatures rise if we continue to emit greenhouse gases at the current rate?

Discussions in the media about global climate change frequently mention climate models, and "model-bashing" is a favorite pastime of climate change skeptics. The term "climate model" may bring to mind the familiar television weather map with its movements of air masses, clouds, and precipitation, but climate models are more mathematical and complex than weather forecasts. Rather than predicting the movements of air masses a few days in advance (which is a challenge in itself—no matter what the Weather Channel says, pack an umbrella just in case), climate models deal with larger regions over longer time scales. A considerable number of factors (in scientific lingo—parameters) must be included in climate models. What are the patterns of greenhouse gas emissions, and what quantity of greenhouse gases can be expected to accumulate during the time period under consideration? How much will each greenhouse gas (carbon dioxide, methane, water vapor, and so on) contribute to warming? How will the increase in concentration of water vapor in the atmosphere affect cloud formation? How will the clouds influence temperature? What will be the concentration of atmospheric particles like soot that can act as seeds to trigger cloud formation? What other effects will the atmospheric particles have? How significantly will the warming reduce ice and snow cover, and how much will the resulting decrease in reflectivity further enhance the heating at the earth's surface? How will the uptake of carbon dioxide by plants and the ocean be affected by warming? How could the warming predictions be affected by other natural sources of climate variation, such as cyclic variations in the sun's output or volcanic activity on Earth? Whew!

The need to take all of these different parameters into account means that climate models require tremendous computational power. Supercomputers are often used to do the number crunching. In addition, developing the climate model is not simply a matter of devising mathematical equations to account for each parameter. None of the values of the parameters is known for certain, and each is the focus of ongoing research. As new data become available, models are updated accordingly. Models must also be tested. The models are used to make predictions about the world, and then refined based on their ability to mimic reality. As a result, models improve with time and further research. Current climate models are better than past models, but because so many factors are still uncertain, predictions of future temperature increases vary widely. The range of these predictions will likely narrow as each of the parameters becomes better understood.

Myth #2

Scientific models are visual representations of reality.

Not usually. Scientists may use models that are scaled down (for example, of the solar system) or scaled up (for example, of a molecule) versions of reality. However, these kinds of models are mostly used for explanatory and teaching purposes. The most important scientific models are those used to make and test predictions about the world.

Implications for making sense of scientific issues:

Biological, meteorological, geological, and other phenomena are highly complex and influenced by large numbers of interacting factors. As a result, predictions made about them are usually given as a range of possibilities, rather than as a single number. The predictions made through modeling should be interpreted with caution but not dismissed just because there is uncertainty associated with them. Scientific models are refined based on how well they can predict the behavior of things in the real world; therefore, models are constantly improving.

What's all this talk about controversy?

In school, students rarely learn to view disagreements among scientists as a natural part of the progress of science; most textbooks are written as if science is a set of truths to be memorized. Teachers, especially in

America, are under enormous pressure to cover a large number of unrelated science topics each year to prepare their students for accountability tests, which generally measure students' ability to recall facts. When breadth is emphasized over depth, there simply is not time to discuss how the scientific ideas came to be. There is barely time to help students grasp the meaning of the ideas themselves. On the rare occasions when students are exposed to historical ideas about science, those ideas tend to be dismissed with minimal discussion of why they were replaced, or why scientists held them in the first place. Students are left with the impression that scientists held some silly ideas in the past, but now they have it all figured out, and today's scientific theories are true.

For folks who have never had the opportunity to learn how disagreements between scientists play a role in the progress of science, it can be confusing or frustrating to be told that scientists disagree about the meaning of a finding, or to find out that scientific advice they had taken to heart (eat margarine instead of butter) has been overthrown (avoid margarine—it's bad for you). However, controversy within science has always been a normal part of the progress of science. Familiarity with past examples of clashes between scientists can help one better understand the science-in-the-making in the media today. The historical example of what came to be the foundational theory on which modern geology is built, though initially proposed by one scientist and rejected by nearly all of his contemporaries, provides insight into how and why revolutions in scientific thinking occur.

Scientific revolutions really happen

In 1912, Alfred Wegener formulated a hypothesis about continental drift. The basic idea of continental drift is that all of the earth's landmasses were once joined together as a supercontinent, Pangaea, which later broke apart, leaving the continents gliding across the substratum. Wegener had several lines of evidence to support his continental drift hypothesis. The outlines of the continents look more or less as though they should fit together like pieces of a jigsaw. The distributions of living things, past and present, have striking similarities on different continents. There are similarities in rock formations on different continents. The distribution of climates was not the same a few hundred million years ago as it is today. Continental drift is an elegant hypothesis that can explain many puzzling observations. Yet many scientists gave it two thumbs down for nearly half a century.

The problem was that Wegener had no plausible mechanism for how continents could drift. It would take huge amounts of energy to move something as massive as a continent, no matter how slowly. How on earth could the continents be moving? Understanding mechanism is a big part of science, and scientists frown on "hand-waving" sorts of explanations, which is all Wegener could come up with based on the data available to him. Wegener himself recognized the gaps in his ideas and acknowledged them in his writing.

Ultimately, it was new data that drove the acceptance of continental drift. Three discoveries were pivotal. First, scientists discovered that the rocks on the ocean floor are much younger than the rocks that make up the continents. Second, they found a long chain of mountains, with active volcanoes along its middle and ancient volcanoes bordering them, that forms a continuous north-south seam in the middle of the Atlantic Ocean. Third, they discovered that there is a pattern of magnetic stripes with alternating polarity—some with their north pole facing north and some with their north pole facing south—along the ocean floor, parallel to the mountain chain beneath the Atlantic. Scientists already knew that, as it cools, molten rock laid down by volcanoes becomes magnetized according to the orientation of the earth's magnetic field, and that the earth's magnetic field has reversed itself several times throughout history. Therefore, the magnetic stripes on the ocean floor suggested that magnetized, solidified rock was pushed aside as new rock—which may have a different magnetic orientation depending on the orientation of the earth's magnetic field at the time—was laid down by volcanic activity. These results are consistent with the idea that volcanic activity between adjacent continental plates caused Pangaea to break apart about 200 million years ago, forming the Atlantic Ocean. The continents on either side of the ocean are still being pushed apart as the Atlantic Ocean widens by a couple inches per year.

Wegener died during a research expedition to Greenland in 1930, about three decades before his ideas about continental drift revolutionized geology. In fact, much of the research that led to key findings about sea floor magnetic stripes and spreading had nothing to do with testing continental drift. The research was going on in the 1950s, during the Cold War, when the United States hoped that studying the sea floor would provide information that would allow it to disguise its own submarines and better detect the Soviet Union's submarines. The nearly universal acceptance of continental drift resulted from the research of many scientists, working in different places on different projects. Eventually, as the pieces came together, the critique of Wegener's ideas as "preposterous" no longer made sense. It was more preposterous to maintain that the arrangement of oceans and continents was immutable in the face of the overwhelming evidence in support of continental drift.

This account of continental drift leaves out work done since the 1960s. The later work has led to a more detailed theory known as **plate tectonics**, which subsumes continental drift and includes much more detail about the forces that drive the movements of the plates. Nonetheless, the lesson is clear. The clash of ideas is not a problem in science, but rather a normal part of scientific progress. In the face of new evidence, a crazy idea can become the foundation for work in a field. It may take time for the evidence to accumulate, especially if tools are not available to test a hypothesis directly, but in the end, it is the data that do the talking.

Disputes are not a sign of science gone wrong

Because people tend to think of science as a slow accretion of ideas, where discord has no place, the existence of disagreements between scientists has been used to attack the theory of evolution. For example, at one point, existing paleontological (fossil) evidence and molecular (genetic) evidence told different stories about from which animals whales had evolved. The genetic evidence suggested that whales and hippopotami were closely related and shared a common ancestor. According to the fossil evidence available at the time, whales and hippos were only distantly related. Antievolutionists pointed to this disagreement as a flaw in science and a reason for rejecting evolutionary theory. At the same time, the paleontologists and molecular biologists were far from satisfied by the lack of agreement between the two types of data. They came up with explanations for why each might be inaccurate. Paleontologists criticized the molecular evidence because genetics cannot be used to compare the many species that have gone extinct, only the living examples of related species (except in rare cases in which well-preserved DNA from extinct species is available). Molecular biologists criticized the fossil evidence as being insufficient because a small percentage of organisms become fossilized and of those that do and are unearthed, the limb bones may not be well preserved. However, there is a significant difference between the approach of the antievolutionists and the scientists. Unlike the antievolutionists, the scientists specified what would be convincing support for one position or the other. In addition, the scientists predicted that the controversy would be resolved when additional evidence, either molecular evidence or fossil evidence, came to light.

Paleontologists eventually discovered fossils of ancient whales that had hind limbs. The hind limbs contained ankle bones that were clearly similar to those of hippopotami and their close relatives. Therefore, the new fossil finds brought the fossil evidence and the genetic evidence on whale evolution into agreement. This example shows that pointing to discord between scientists as indicative of a weakness in science is misguided. Scientists point out discord themselves. They seek evidence that will help them resolve the discord. Discord arises because science is a work in progress. The scientific process is healthy when scientists are willing to reconsider their ideas in the light of new evidence. While it is completely sensible to draw attention to discord to highlight where more research is needed, it is not sensible to use discord between scientists as a reason to throw one's hands in the air and give up on science.

Living organisms, earth processes, and the evolution of the universe are so complex that the existence of discord in science should not be puzzling. Even problems that seem straightforward, such as the relationship between estrogen levels and hot flashes, invariably turn out to be more complex when investigated thoroughly. Many women experience hot flashes—a feeling of intense heat often accompanied by flushing and sweating and sometimes followed by chills—as they approach and transition through menopause. Since estrogen levels decrease at menopause, and since estrogen supplements alleviate hot flashes, it is logical to assume that low estrogen levels trigger hot flashes. Some studies are consistent with this hypothesis, but others are not. While considered the hallmark of the menopausal transition, hot flashes can occur at other times of life and can affect both women and men. In addition, not all women experience hot flashes during menopause. Plus, some women who have low estrogen levels—for example, gymnasts or endurance athletes—do not experience hot flashes. These conflicting data have forced researchers to reconsider the role of estrogen in hot flashes. They hypothesize that hot flashes may not be triggered by low estrogen, but rather by estrogen levels that are in the process of declining. In other words, the cause may be the change in estrogen levels (dynamic) over time, not the absolute (static) level of estrogen at any point in time. Gathering the data to test the new hypothesis is trickier than gathering the data to test the original hypothesis. It requires following women over time to determine how their estrogen levels change and how the changes influence hot flashes. Long-term studies are expensive, time consuming, and challenging. In addition, other hormones and health and lifestyle factors likely play a role in who gets hot flashes. Since many experiments are needed to tease apart the complexities of an issue like the relationship between estrogen and hot flashes, it would be more surprising if conflicting ideas never arose in science and each new factoid was simply added on top of a pile of existing knowledge.

Myth #3

Science is the progressive accumulation of new facts.

No. If it were this simple, new information would accumulate, but old ideas would not be overthrown. In fact, revolutions in scientific thought do take place.

Implications for making sense of scientific issues:

We should base our decisions on today's scientific knowledge because it is the very best we have, collected with the most powerful tools available, and rooted in the work of generations of scientists. However, we must keep our minds open to the possibility that policies and courses of action may need to be altered in the face of contradictory evidence.

The media often misrepresents disputes between scientists

Disagreements between scientists are a normal part of the process of science, but the media often exaggerates, misrepresents, or oversimplifies these disputes to sensationalize the latest science news. This is especially common in headlines or brief sound bites. For example, there is new and still disputed evidence that moderate amounts of sun exposure may reduce a person's chances of getting certain internal cancers like breast, endometrial, colon, and prostate cancer. It is not hard to imagine the headlines and sound bites proclaiming, "scientists now say sun is good for you!"

Let's dissect this claim. On the surface, one could argue that it is accurate: Anything that reduces your risk of getting cancer is good. However, everyone knows that too much sun exposure can lead to skin cancer. So are scientists now disputing that? No. Is it possible that sun exposure could increase your risk of skin cancer, but decrease your risk of some internal cancers? Yes. Ultraviolet light from the sun can cause skin cancer by damaging DNA in skin cells, and this can ultimately cause cells to start multiplying out of control. Cancer is the result of the uncontrolled proliferation of cells. The proposed mechanism by which sun exposure might protect you from internal cancers is completely different. Exposure to the sun allows your body to synthesize vitamin D, and possibly other important compounds. Vitamin D, among other functions, may help prevent overproliferation of cells.

One obvious question is why sun exposure does not protect you from skin cancer if vitamin D can stop cells from proliferating out of control. It may be that the risk of bombarding the DNA in your skin cells with ultraviolet radiation from the sun outweighs the benefit of having a little extra vitamin D around. On the other hand, the sun's UV rays do not penetrate all the way through your skin, so your internal organs could benefit from the protective effects of extra vitamin D without the negative effects of UV radiation on their DNA.

For at least three reasons, this debate is much more complex than the headline might lead one to believe. First, scientists are still disputing whether it is true that sun exposure can protect you from internal cancers. The evidence for the claim is epidemiological data—the comparison of disease rates in different populations—which is useful but has many weaknesses. People who live in places where they get more sun likely have other lifestyle differences, such as diet and exercise, than their cold weather-dwelling counterparts. Second, even if the claim holds up, there still remains a tradeoff between increasing your risk of skin cancer while decreasing your risk of internal cancers. Third, those who believe sun exposure may protect you from internal cancers are not encouraging people to fry themselves in the sun. The body tightly controls vitamin D synthesis, and maximal synthesis may come after as little as 10 minutes in the sun, depending on the latitude, time of year, and your skin tone. So synthesizing enough vitamin D might be feasible without a significant increase in the risk of skin cancer. At this time, the jury is still out.

This example reveals the weaknesses of relying on sound bites as news. The headline "scientists now say the sun is good for you," might be used by some as a reason to lie out longer at the beach and/or to stop bothering to use sunscreen. On delving deeper into the evidence, it becomes clear these reactions would not be merited *even if* the relationship between sun exposure and reduced risk of internal cancers had been proven beyond a shadow of a doubt. Headlines and sound bites may give the impression that the disputing scientists share little common ground, when in fact, the dispute is often much more specific. In this example, the benefit of sun exposure in preventing internal cancers is under dispute; the risk of skin cancer from sun exposure is not. In the previous example, the scientists were not disputing that evolution occurred or that whales evolved from land animals; only what specific land animal is ancestral to whales was under dispute. Therefore, it is important to determine the extent of the disagreement between scientists before drawing conclusions about claims.

Another problem is what sociologist Christopher Toumey referred to as **pseudosymmetry of scientific authority**—the media sometimes presents controversy as if scientists are evenly divided between two points of view, when one of the points of view is held by a large majority of the scientific community. For example, until recently, the media often gave equal time and space to the arguments for and against humans as the cause of global climate change. Surveys of individual climate scientists have indicated that there is discord among scientists on the issue, but that the majority of scientists agree that humans are altering global climate. One analysis of a decade of research papers on global climate change found no papers that disputed human impacts on global climate. Also, all but one of the major scientific organizations in the United States whose members have expertise relevant to global climate change, more than a dozen organizations in all, have issued statements acknowledging that human activities are altering the earth's climate. The American Association of Petroleum Geologists dissents. Therefore, there is a general consensus within the scientific community that humans are causing global climate change. While it is legitimate to explore the arguments against the consensus position on global climate change, it is misleading for the media to present the issue so as to give the impression that the scientific community is evenly divided on the matter.

Myth #4

Disputes between scientists are an indication that there is a problem with the scientific process.

Not at all. It is normal and healthy for scientists to challenge each other's methods and conclusions.

Implications for making sense of scientific issues:

If disagreements between scientists are viewed as a breakdown of the scientific process, then it is easy to say, "scientists don't know anything anyway," and stop engaging in sense making. Beware of anyone who uses the fact that scientists disagree to denigrate science. On the other hand, if you hear "scientists now think…" you should wonder whether there is still controversy. What do the scientists agree on and what is still up for dispute? Headlines often misrepresent controversy, either inventing controversy where there essentially is none, or brushing over controversy to make a definitive statement when a more cautious statement is more appropriate. When trying to make a decision about voting, health care, nutrition, buying a new car, and so on, it is important to go beyond these sound bites to determine what is and is not under dispute.

From watering hole to prime time—birth and development of an idea

Interactions between scientists, and not just disputes, play a key role in the progress of science. However, nonscientists rarely are privy to the interactions between scientists, and scientists are often stereotyped as loners. Most everyone has heard a story about a scientist coming up with some amazing insight out of the blue. Probably the most famous such story was about Archimedes leaping from his bath, and running naked through the streets shouting, "Eureka!" (I have found it!) As the story goes, he had been looking for a way to help the king determine whether his new crown was made of pure gold, or if an unscrupulous jeweler had duped him by incorporating some amount of a lesser metal. Archimedes noticed the water overflowing as he got into his bath, and it occurred to him that an object submerged in water displaces a volume of water equal to the volume of the object. He also realized that a gold crown would have a smaller volume than a crown of equal mass constructed of a less dense metal like silver, or an alloy of gold and silver. So if the crown displaced more water than would an equal mass of gold, the king had been duped. Archimedes was so excited about his discovery that he forgot his tush was bare.

Scientists rarely work in isolation

Whether the story about Archimedes' eureka moment is true or not, it does reflect the stereotype of the brilliant scientist working alone to come up with a solution to a problem. Many scientists, and nonscientists alike, experience these sorts of "ah ha" moments while lost in their own reflections, sometimes even when they are taking a shower. Fortunately, not too many of them feel compelled to run around in their birthday suits proclaiming it to the world. However, while scientists work individually on certain tasks, they rarely do their work entirely in isolation. Neither folklore, nor textbooks, nor the media give much insight into the many levels of interactions among scientists that are so vital to the progress of science.

One form of interaction is informal brainstorming with colleagues. Like everyone else, scientists like to sit around and chew the fat. While a lot of this talk has nothing to do with science, not infrequently the conversation will get around to someone's current research project, and the brainstorming will begin. It may explore what the results of an experiment mean, what experiment to try next, or even something as banal as where to procure a necessary device or chemical. If there is a whiteboard, blackboard, or chart paper in the room, it will soon be covered with words, graphs, pictures, and formulae. Lack of a surface to write on is no deterrent. Napkins, backs of envelopes, and paper placemats will do the trick, and if restaurant crayons are the only writing implements available, so be it. The written artifacts resulting from the discussion will simply be more colorful. Bouncing ideas off colleagues is a great way to get a fresh perspective on one's own research because, after focusing on a problem for a while, it is sometimes hard to see the forest for the trees. Also, since individual scientists read different papers and attend different lectures and conferences, they may come across research potentially relevant to their colleagues. Furthermore, in other phases of science, scientists are expected to have sufficient evidence to back up their claims, but brainstorming with colleagues is an opportunity to get feedback on the hunches and crazy ideas that can sometimes end up revolutionizing a field. Exciting new ideas emerge when a bunch of bright people get together, listen to each other, and ask "what if?"

These informal discussions between scientists are so important that science buildings are often designed with common "watering holes," where people go for coffee breaks or to wait for an experiment to run to completion. Different labs may share this common area, and, when feasible, buildings are planned to place research groups with complementary research interests in proximity of each other. Of course, collaboration among colleagues is not restricted to science. Many businesses design space to facilitate informal interactions among employees, recognizing that this stimulates innovation.

Answering complex scientific questions also requires more formal interactions among people with different types of expertise. For example, determining how acid rain is affecting a forest would require a biologist who knows about plant metabolism and is able to gauge the health of the trees, and a chemist who understands how chemicals in the soil (for example, metals) react under acidic conditions and is able to perform tests on soil chemistry. A geologist's input about the types of rocks found in the area would also be valuable because different rocks (for example, limestone versus granite) are composed of different chemicals, which react differently with acid. It is therefore common for interdisciplinary teams of scientists to work together on grant proposals, projects, and papers. Even when scientists do not work together from the start of an investigation, a published study that identifies a problem—such as a new disease afflicting trees—may lead another scientist to build on the work by trying to gain insight into a possible contributing factor to that problem—such as changes in soil chemistry.

Scientists also constantly rely on tools and procedures that have been developed by other scientists. When scientists publish their results, they must carefully describe how they did the research. Published procedures are important to the progress of science because they ensure that scientists do not have to reinvent the wheel each time they want to do a new experiment. Perfecting experimental procedures is challenging and time consuming. For example, it may take months for a team of researchers to determine how to culture—grow—cells in the laboratory. Many different factors must be optimized. The cells will require special nutrients, as well as hormones and other chemicals that they would normally be exposed to in the body. Trial and error is used to determine the ideal composition of the culture medium—broth—to keep the cells healthy. Even the plates used to grow the cells must be perfected. The cells may not grow unless the plates are coated with a substance to which the cells can adhere. Finding a substance that is nontoxic and facilitates normal cell growth and division may also require trial and error. By publishing the composition of the culture medium and plate coating that promotes healthy cell growth and division, the researchers save other researchers countless hours of work, and make the scientific process much more efficient. It is not because of altruism that the researchers who do all the work to perfect a procedure make it available to everyone else. When the researchers publish a paper describing a procedure, it will be referenced in the papers of everyone who uses it. The publication of papers that are influential helps the researchers gain promotions, awards, and research funding.

Critique is very important in the publication process

While a scientist is coming up with a hypothesis to test, developing a way to test the hypothesis, and interpreting the results, close-working colleagues will provide cycles of review and feedback. Colleagues propose alternative hypotheses. They provide advice about how best to test the hypothesis, or help troubleshoot if technical difficulties arise with the experimental procedure or equipment. They suggest alternative ways of analyzing the data, such as more rigorous statistical tests. They may disagree with the conclusions drawn from the data and suggest other experiments that could be used to distinguish between alternative conclusions. If the findings hold up to scrutiny at this internal review level, then they are ready for the critical eye of outside scientists. In an academic setting—a university or other not-for-profit research center—scientists are expected to present their work at conferences and publish in peer-reviewed journals. "Publish or perish" is what young researchers are told. Scientists working in industry may also publish papers or present their results at scientific conferences, but industry scientists are often forced to keep critical aspects of their results private to protect proprietary knowledge, such as what chemicals and procedures are used to make a product or what compounds show promise toward becoming the next blockbuster drugs.

Results presented at scientific conferences are usually more preliminary than those presented in peer-reviewed journals. To give a talk at a conference, scientists, except invited speakers, must submit a summary of the findings they want to present. If the findings seem sufficiently interesting and believable to the reviewers—who are usually other scientists in the same field—the scientist will be allowed to present. Conferences give scientists the opportunity to network with colleagues at other institutions, potentially helping them set up new cross-institutional collaborations, and to get feedback that helps them prepare their work for publication in a peer-reviewed journal.

When a scientist submits a paper to a journal for publication, the journal's editor usually sends it to three independent reviewers who make comments, ask questions, and express their concerns. The reviewers may request that the scientist do more experiments, and/or challenge the scientist's interpretation of the results. The scientist can address the concerns of the reviewers and then resubmit the paper to the journal, unless the journal completely rejects the paper because of real or purported flaws in the science, or because the editor does not believe the paper fits with the theme of that particular scientific journal. There can be several phases of editing and review before a paper is published, and some papers will never make it to publication if the scientist cannot adequately respond to the concerns of the reviewers. The review process serves as quality control to prevent the publication of unsubstantiated claims. However, like any quality control process, it sometimes rejects outstanding work, and sometimes permits shoddy work to get through. As discussed later in the chapter, papers that are simply "before their time" may be rejected by the journal or, even if published, ignored by the scientific community. On the other hand, papers containing fraudulent data may make it past the reviewers and be published.

These flaws, while serious, need to be kept in perspective. In particular, they are not arguments against the importance of the scientific review process. A scientist's attempt to bypass peer review by pitching a claim directly to the media is a serious warning sign of possible intellectual dishonesty. If a discovery is exciting and the data are sound, the research should merit publication in a major scientific journal. It may get published in *Science*, *Nature*, or another journal that prints articles from all fields of science, or it may get published in one of the field-specific journals, such as *Cell*, the *Journal of the American Chemical Society*, or the *British Medical Journal*. Either way, the published article will include a detailed description of the procedure that the researchers followed to collect the data. In contrast, when reporters from the mainstream media or popular science journals write about discoveries for the general public, they tend to skim over the details about the methods used by the researchers. Popular accounts of scientific discovery are therefore considerably more palatable than research articles in scientific journals, but they do not contain adequate information for other scientists working in the field. Without detailed information about experimental procedures, other researchers are unable to determine whether there could be an alternative explanation for the results. They also cannot replicate the results. Ultimately, it is the replication of results by other researchers that is the test of the results' validity. Publication is not the final stage of the scientific process because when the review process fails to keep bunk from being published, future research sheds light on the error.

Arguably the most infamous example of results that were pitched directly to the media, only to turn out to be spurious, is the case of cold fusion. In the spring of 1989, Stanley Pons and Martin Fleischmann held a news conference to make the stunning announcement that they had managed to fuse atoms of deuterium at room temperature without using expensive equipment. Nuclear fusion provides the energy that powers the sun, and achieving nuclear fusion on Earth at low temperatures would be a major achievement. It would permit unlimited amounts of energy to be produced cheaply. Not surprisingly the cold fusion announcement created a hubbub within the scientific community and among the general public. The month after the announcement by Pons and Fleischmann, the American Chemical Society organized a symposium on cold fusion at its national conference. The symposium attracted 7,000 people, not a large number for a rock concert, but a huge draw for a set of talks about science. Two decades later, we do not have any cold fusion devices powering our homes or cars, nor are any on the horizon, although a small band of researchers is still working on the topic. The majority of researchers have written off cold fusion as a mistake, or outright fraud. Because Pons and Fleischmann announced their cold fusion results to the media without publishing them in a scientific journal, and they were secretive about their methods, it took time for other researchers to come to the conclusion that the signs of fusion Pons and Fleischmann claim to have seen were the result of experimental errors. Had their results been subjected to peer review before their announcement to the media, these errors would very likely have been identified before cold fusion fever spread worldwide.

In general, there is nothing wrong with scientists talking to reporters about their research. Many scientists want to teach the public about their work to inspire young people to study science and to convince taxpayers of its value. Some public funding agencies, such as the U.S. National Science Foundation, even mandate that the scientists who receive funding from them engage in activities to inform the public about their research. The problem only arises when scientists promote their research to the media in lieu of publishing it in a scientific journal, or when they make claims that go far beyond those that are supported by existing scientific research. Some scientific journals even have rules prohibiting scientists from talking to the media until right before the scientist's paper is going to be published by the journal. These rules are referred to as the **embargo policy**. The purpose of the embargo is to avoid a cold fusion-like scenario by making sure a research paper is available for critique by other scientists when the popular press is reporting on the story. Therefore, claims should be interpreted with extreme caution if they have been made directly to the media, especially if other scientists are greeting them with skepticism.

Myth #5

The publication of findings is the endpoint of the scientific process.

No. In some ways, publication is the beginning because it allows other scientists to build on the work. It also exposes the work to the scrutiny of any scientist around the world.

Implications for making sense of scientific issues:

In considering the veracity of scientific findings, studies published in a scientific journal should be given infinitely more weight than those that are not, but beyond that, time is the most critical test.

The age of an idea is not proof of its accuracy, but ultimately time for further research is needed to confirm or disconfirm findings. A finding should be given more weight if there are multiple confirming instances, if the confirming instances were observed under many different conditions, and if some of the findings have disconfirmed alternative hypotheses. Also, a hypothesis is considered much stronger if it successfully predicts future observations, rather than merely accounting for existing observations.

The scientific review process is not flawless

The many levels of critique give the scientific process its strength, but no process is perfect. Sometimes good science does not get published, and sometimes bad science does.

Revolutionary ideas are sometimes overlooked

Barbara McClintock's research on "jumping genes," or **transposons**—bits of DNA that can move from one place on a chromosome to another—is an example of important science that initially failed to garner the attention it deserved. McClintock had collected reams of data to support her claims about transposons. She had meticulously documented how color changes in the kernels of the corn plants she bred could be linked to the changes in the chromosomes of those plants as seen through a microscope. She knew that her findings would come as a surprise to her fellow biologists, so before making them public, she spent six years collecting data to refute the objections to her findings that she anticipated other researchers would have. However, the field of genetics had not yet advanced to the point where it could provide a real mechanism for McClintock's observations.

It took more than 20 years from the time she made her research on transposons public to its recognition by the greater scientific community. This lack of acceptance could not be attributed to the marginalization of McClintock; she was already well known for her work on the genetics of corn. Also, some other corn geneticists did recognize the importance her work, and a few even had similar findings. The problem was that in the early 1950s, when McClintock first made her work public, biologists took for granted that genes were stable. It seemed unfathomable to think that genes could jump around on a chromosome—just as scientists did not initially believe that the continents could be moving.

New data and an explanatory mechanism led other scientists to accept that transposons were real and to recognize their significance. In the decades between the initial announcement of her findings and the research community's acknowledgement of their importance—ultimately earning her a Nobel prize—other research, including Watson and Crick's determination of the structure of DNA, and independent confirmation in bacteria of the sort of gene rearrangements McClintock had discovered, led to a sea change in the way scientists think about genetics. They stopped viewing genes as simply beads on a string—a chromosome—and in the face of volumes of data collected by independent researchers working on different problems, the notion that genes can move around came to be accepted.

The many historical examples of the scientific community ignoring ideas that are before their time, like those of Wegener and McClintock, are often exploited by cranks to argue in favor of their implausible schemes. Their arguments run as follows:

> *The scientific community is not accepting my revolutionary idea about ______ (insert topic) just as ______ (name of a famous scientist) was ignored by his/her contemporaries. Time will vindicate me, just as ______ (famous scientist) was vindicated. In the meantime, you can benefit from buying my ______ (name of product or book).*

The problem with this argument is that while a number of scientists have been ignored and later vindicated, these examples are still relatively rare compared to all of the examples of individuals who put forth crazy ideas that have not been vindicated. The earth is flat. The earth is hollow. Maggots are spontaneously generated by rotting meat, and mice are spontaneously generated by linens sprinkled with a few grains of wheat. The bumps on people's skulls provide insight into their personalities and capabilities. Christ was an astronaut who traveled back in time in a yet-to-be-developed NASA time machine. The likelihood that the ideas of self-proclaimed revolutionaries will end up on the crazy idea junk heap—along with flat Earth, hollow Earth, spontaneous generation, phrenology, and deity in a spaceship, respectively—is much greater than the likelihood that their ideas will revolutionize science. For that reason, the claim that revolutionary ideas are sometimes overlooked, while true, is a poor argument for the legitimacy of an idea.

Myth #6

Many important ideas have been ignored in the past, so if someone claims to have ideas that are being ignored by the scientific establishment, there is a good chance that their ideas are correct.

No. For every outlandish-sounding idea that is later vindicated, hundreds of others will never be anything but bunk.

Implications for making sense of scientific issues:

As the famous astronomer Carl Sagan said, "Extraordinary claims require extraordinary evidence." Any purported discovery that overturns well-accepted theories of how the world works should be greeted with healthy skepticism, especially if it is based on anecdotal evidence and the discoverer is not even an expert in the field. Unpublished findings are not a good basis for making important decisions. Despite the problems with the scientific review process sometimes missing hot science and sometimes letting fraudulent science through, it is still the best mechanism that exists for evaluating the validity of claims. The scientific community is diverse, and it is highly improbable that the entire community would or could conspire against an individual. Alfred Wegener and Barbara McClintock knew that their colleagues would view their respective ideas about moving continents and jumping genes with skepticism. Neither claimed that the scientific community was conspiring against them because of it. In fact, they were both just as troubled as the rest of the scientific community by the lack of a plausible mechanism to explain their findings.

Fraud sometimes occurs

In addition to sometimes turning a blind eye on revolutionary ideas, reviewers and the rest of the scientific community can get tricked into believing bogus results. In 2002, scandal rocked the world of physics. Starting in the late 1990s, Jan Hendrik Schön, a young physicist from

Germany working at the world famous Bell Laboratories in New Jersey, and his colleagues there, published a string of papers that promised to revolutionize several fields. Just before the investigations into their work brought everything crashing down, the group was publishing at the remarkable rate of one paper every eight days, mostly in major journals. The researchers had been working on tiny electrical switches similar to the ones used in computers. They developed switches from a variety of materials and discovered that the switches had surprising properties. For example, by adding a very thin coating of the chemical aluminum oxide to the switches, they could get materials that were usually poor at conducting electricity to conduct it very well. This may not sound particularly exciting, but Schön's papers were among the most cited papers in physics, and had scandal not erupted, his work would have very likely earned him a Nobel Prize.

But on May 10, 2002, officials at Bell Labs launched an investigation of Schön's work after outside researchers noticed what appeared to be a duplication of data in multiple papers. Even before the discovery of duplicated data in Schön's papers, scientists were starting to raise questions about why other labs were not able to replicate many of Schön's amazing results, despite their efforts and the tens of millions of dollars being spent on research in the area. On September 25, 2002, a Bell Labs report concluded that Schön had committed widespread misconduct.

A few years after the scandal over Schön's research, Woo Suk Hwang, a South Korean researcher who published pioneering work on producing patient-specific stem cell lines, was found guilty of fabricating data. Again, the problems with the work were revealed when other scientists scrutinized it and attempted to replicate it after its publication. When scientists want to pursue a particular line of work, they check their materials, equipment, and procedures by comparing their results to the published results from an identical experiment by another scientist. If time passes and other researchers cannot get the experiments to work, the original research will fall under scrutiny. Both Schön and Hwang were on the cutting edge of very hot fields. They should have known that they would eventually be found out. Had they been working on some obscure problem, it may have taken much longer for their work to have been exposed as fraudulent. On the other hand, they would not have had the excitement of making headlines on a regular basis. We will probably never know why they acted unethically, but in the end, their careers were ruined. In an unprecedented move, the institution from which Schön earned his doctorate revoked his Ph.D., although there was no evidence he had fabricated any of that research.

Although these are examples of pathological science, in the end, time and scrutiny by the scientific community did get science back on course again. McClintock's story shows that time and the accumulation of evidence can vindicate the work of the maverick. Schön's and Hwang's stories show that it can also expose the charlatan. The examples of McClintock's, Schön's, and Hwang's work reveal what Evelyn Fox Keller, in her biography of Barbara McClintock, *A Feeling for the Organism*, referred to as the "tangled web of individual and group dynamics" that defines the growth of scientific knowledge. Indeed, individuals cannot push scientific knowledge forward alone; it is through multiple levels of interactions between the individual and the group that science advances.

As Harry learned from the Half-Blood Prince's potions book, there is a lot more to doing science than following a recipe. This chapter took that lesson further by laying bare the inner workings of the scientific process. However, Harry, Ron, and Hermione also learned that making potions was one thing, using potions on their adventures was another. Their adventures exploited Felix Felicis and Polyjuice Potion the way people who hold stake in an issue exploit scientific results for their own purposes. The production of scientific results is just the beginning of the plot. The adventure continues after the results are made public. The subsequent chapters of this book explore the twists and turns of plot that occur once scientific results make it into the public realm.

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