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Science Matters

Achieving Scientific Literacy

Robert M. Hazen and
James Trefil

Science Matters

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To Margee and Wanda

INTRODUCTION

Scientific Literacy: What It Is, Why It’s Important, and Why We Don’t Have It

SOME TIME IN THE NEXT few days you are going to pick up your newspaper and see a headli like “Major Advance in Stem Cells Reported” or “New Theory of Global Warmi Proposed.” The stories following these headlines will be important. They will deal with issu that directly affect your life—issues about which you, as a citizen, will have to form a opinion if you are to take part in our country’s political discourse. More than ever befor scientific and technological issues dominate, from global climate change, to the teaching evolution, to the perceived gradual decline of American competitiveness. Being able understand these debates is becoming as important to you as being able to read. You must b scientifically literate.

In spite of decades of well-meaning efforts, scientists and educators have failed to provi many Americans with the fundamental background knowledge we all need to cope with th complex scientific and technological world of today and tomorrow. The aim of this book is allow you to acquire that back-ground —to fill in whatever blanks may have been left b your formal education. Our aim, in short, is to give you the information you need to becom scientifically literate.

What Is Scientific Literacy?

For us, scientific literacy constitutes the knowledge you need to understand public issues. It a mix of facts, vocabulary, concepts, history, and philosophy. It is not the specialized stuff the experts, but the more general, less precise knowledge used in political discourse. If yo can understand the news of the day as it relates to science, if you can take articles wi headlines about stem cell research and the greenhouse effect and put them in a meaningf context—in short, if you can treat news about science in the same way that you tre everything else that comes over your horizon, then as far as we are concerned you a scientifically literate.

This definition of scientific literacy is going to seem rather minimal, perhaps even total inadequate, to some scholars. We feel very strongly that those who insist that everyone mu understand science at a deep level are confusing two important but separate aspects scientific knowledge. The fact of the matter is that *doing* science is clearly distinct from *usi* science; scientific literacy concerns only the latter.

There is no need for the average citizen to be able to do what scientists do. You don't hav to know how to design a microchip or sequence a section of DNA to understand the dai news, any more than you have to be able to design an airplane in order to understand how can fly.

But the fact that you don't have to know how to design an airplane doesn't change the fa that you live in a world where airplanes exist, and your world is different because of them. the same way, advances in fields like nanotechnology and bioengineering will affect your li in many ways, and you need to have enough background knowledge to understand how the changes are likely to occur and what their consequences are likely to be for you and you children. You must be able to put new advances into a context that will allow you to tak part in the national debate about them.

Like cultural literacy, scientific literacy does not refer to detailed, specialized knowledge- the sort of things an expert would know. When you come across a term like "superconducto in a newspaper article, it is enough to know that it refers to a material that conduc electricity without loss, that the main impediment to the widespread use of superconducto is that they operate only at very low temperatures, and that finding ways to remove th impediment is a major research goal in materials science today. You can be scientifical literate without knowing how a superconductor works at the atomic level, what the vario species of superconductor are, or how one could go about fabricating a superconducti material.

Intense study of a particular field of science does not necessarily make one scientifical literate. Indeed, it has been our experience that working scientists are often illiterate outsi their own field of professional expertise. For example, when we asked a group of two doze physicists and geologists to explain to us the difference between DNA and RNA, a basic pie of information in the life sciences, we found only three who could do so, and all three those did research in areas where this knowledge was useful. And although we haven't do an equivalent test on biologists—by asking them, for example, to explain the differen between a superconductor and a semiconductor—there is no doubt in our minds that w would find the same sort of discouraging result if we did. The fact of the matter is that th education of professional scientists is often just as narrowly focused as the education of a other group of professionals, and scientists are just as likely to be ignorant of scienti matters as anyone else. You should keep this in mind the next time a Nobel laureate spea ex cathedra on issues outside his or her own field of specialization.

Finally, one aspect of knowledge is sometimes lumped into scientific literacy but is actual quite different. You sometimes see discussions of scientific literacy couched in terms statements like "The average new employee has no idea how to use a BlackBerry" or "T average American is dependent on technology but can't even program a DVR to record wh no one's home." These statements are probably true, and they undoubtedly reflect unhappy state of affairs in American society. We would prefer, however, to talk of them terms of *technological* rather than scientific literacy.

The Scope of the Problem

The effectiveness of American science education has changed little since the 198 commencement of Harvard University, when a filmmaker carried a camera into the crowd o gowned graduates and, at random, posed a simple question: "Why is it hotter in summer tha in winter?" The results, displayed graphically in the film *A Private Universe*, were that on two of the twenty-three students queried could answer the question correctly. Even allowin for the festive atmosphere of a graduation ceremony, this result reveals the failure o America's most prestigious universities to turn out students who are in command o rudimentary facts about the physical world. An informal survey taken at our own universit —where one can argue that teaching undergraduates enjoys a higher status than at som other institutions—shows results that are scarcely more encouraging. Fully half of the senio who filled out our scientific literacy survey could not correctly answer the question "What the difference between an atom and a molecule?"

These results are not minor blemishes on a sea of otherwise faultless academ performances. Every university in the country has the same dirty little secret: we are a turning out scientific illiterates, students incapable of understanding many of the importa newspaper items published on the very day of their graduation.

The problem, of course, is not limited to universities. We hear over and over again abo how poorly American high school and middle school students fare when compared to studen in other developed countries on standardized tests. Scholars who make it their business t study such things estimate that fewer than 7 percent of American adults can be classed a scientifically literate. Even among college graduates (22 percent) and those with gradua degrees (26 percent), the number of Americans who are scientifically literate by th standards of these studies (which tend to be somewhat less demanding than our own) is no very high.

The numbers, then, tell the same story as the anecdotes. Americans as a whole simply hav not been exposed to science sufficiently or in a way that communicates, the knowledge the need to have to cope with the life they will have to lead in the twenty-first century.

Why Scientific Literacy Is Important

Why be scientifically literate? A number of different arguments can be made to convince yo it's important. We call them,

the argument from civics
the argument from aesthetics
the argument from intellectual connectedness

The first of these, the argument from civics, is essentially the one we have been using thu far. Every citizen will be faced with public issues whose discussion requires some scientif background, and therefore every citizen should have some level of scientific literacy. Th threats to our system from a scientifically illiterate electorate are many, ranging from th danger of political demagoguery to the decay of the entire democratic process as vit decisions that affect everyone have to be made by an educated (but probably unelected) elit

The argument from aesthetics is somewhat more amorphous, and is closely allied t arguments that are usually made to support liberal education in general. It goes like this: W live in a world that operates according to a few general laws of nature. Everything you c from the moment you get up to the moment you go to bed happens because of the working o one of these laws. This exceedingly beautiful and elegant view of the world is the crownin achievement of centuries of work by scientists. There is intellectual and aesthetic satisfactio to be gained from seeing the unity between a pot of water on a stove and the slow march o the continents, between the colors of the rainbow and the behavior of the fundament constituents of matter. The scientifically illiterate person has been cut off from an enrichin part of life, just as surely as a person who cannot read.

Finally, we come to the argument of intellectual coherence. It has become a commonplac to note that scientific findings often play a crucial role in setting the intellectual climate of a era. Copernicus's discovery of the heliocentric universe played an important role in sweepin away the old thinking of the Middle Ages and ushering in the Age of Enlightenment. Darwin discovery of the principle of natural selection made the world seem less planned, le directed than it had been before; and in the twentieth century the work of Freud and th development of quantum mechanics made it seem (at least superficially) less rational. In a of these cases, the general intellectual tenor of the times—what Germans call the zeitgeist- was influenced by developments in science. How, the argument goes, can anyone hope t appreciate the deep underlying threads of intellectual life in his or her own time withou understanding the science that goes with it?

What to Do

The beginning of a solution to America's problem with scientific literacy, both for those st in school and those whose formal education has been completed, lies in a simple statement:

If you expect someone to know something, you have to tell him or her what it is.

This principle is so obvious that it scarcely needs defending (although you'd be amazed how often it is ignored within the halls of academe). It's obvious that if we want people to b able to understand issues involving genetic engineering, then we have to tell them wh genetic engineering is, how DNA and RNA work, and how all living systems use the sam genetic code. If we expect people to come to an intelligent decision on whether tens o billions of tax dollars should be spent on alternatives to fossil fuels—development of biofuel new nuclear power plants, wind turbines, and the like—then we have to tell them about th nature of energy in general and the potential benefits and risks associated with each specif energy source.

But this argument, as simple as it seems, runs counter to powerful institutional forces in th scientific community, particularly the academic community. To function as a citizen, yo need to know a little bit about a lot of different sciences—a little biology, a little geology, little physics, and so on. But universities (and, by extension, primary and secondary school are set up to teach one science at a time. Thus, a fundamental mismatch exists between th kinds of knowledge educational institutions are equipped to impart and the kind o knowledge the citizen needs.

So scientists must define what parts of our craft are essential for the scientifically litera citizen and then put that knowledge together in a coherent package. For those still in schoo this package can be delivered in new courses of study. For the great majority of Americans-those whom the educational system has already failed—this information has to be mac available in other forms.

And that's where this book comes in.

About the Book

This book is dedicated to illustrating a statement that is one of academe's best-kept secret *The basic ideas underlying all science are simple*. In what follows, we present only th constellations of basic facts and concepts that you need to understand the scientific issues the day.

Science is organized around certain central concepts, certain pillars that support the enti structure. There are a limited number of such concepts (or "laws"), but they account f everything we see in the world around us. Since there are an infinite number of phenome and only a few laws, the logical structure of science is analogous to a spider's web. Sta anywhere on the web and work inward, and eventually you come to the same cor Understanding this core of knowledge, then, is what science is all about.

The organization of this book reflects the weblike organization of science. It is built arour nineteen general principles—call them laws of nature, great ideas, or core concepts if yo like. Some of them transcend the compartmentalized labels we like to put on things, for, lik nature itself, these great ideas form a seamless web that binds all scientific knowled together. We devote the first five chapters of the book to these concepts, which will reappe in the remainder. They are absolutely essential to understanding science. You can no mo study genetics while ignoring the laws of chemistry than you can study language by learni nouns and ignoring verbs.

Once the basic concepts that anchor all science have been established, we move on to loo at specific areas, which we have organized in the traditional triad of physical, earth, and li sciences. We organize each of these categories around another set of great ideas that a appropriate to that particular field. For example, in the earth sciences one of the great ide has to do with the changes of the planet's surface features in response to heat generated in i deep interior. This particular concept ties together a great deal of what we know about th earth, but at the same time depends on the deeper overarching principles contained in th first five chapters. By the time you've gone through all nineteen great ideas, then, you wi have not only a general notion of how the world works, but also the specific knowledge yo need to understand how individual pieces of it (the earth's surface, for example, or a stra of DNA) operate.

The great ideas approach to science has another enormous advantage. While you a learning about issues that are in the news today, such as drug-resistant microbes or huma cloning, you will be building an intellectual framework that will allow you to understand th issues of the future. To see the importance of this approach, consider that when we fir began discussing this second edition of *Science Matters* in 2006, the reality of global warmi (and the consequent need for governmental action) was still hotly debated in political circle A year later, thanks in part to record temperatures and an unprecedented shrinking of th Arctic ice cap, the reality of global warming is widely accepted and the debate has shifted determining how much of the warming is caused by human activities and what actions nee to be taken to deal with it.

It is entirely possible that problems that loom large today—the spread of bird flu, th ethics of stem cell research, the proliferation of nuclear weapons, and much more—may see insignificant by 2020. But while we cannot predict *which* science-laden issues will domina the headlines of the future, we know that some surely will. And since every future scientif advance will grow out of the ideas contained in this book, mastering them allows you to de with not only today's problems, but tomorrow's as well.

There is a temptation, when presenting a subject as complex as the natural sciences, present topics in a rigid, mathematical outline. We have tried to resist this temptation for number of reasons. In the first place, it does not accurately reflect the way science is actuall performed. Real science, like any human activity, tends to be a little messy around the edge More important, the things you need to know to be scientifically literate tend to be somewhat mixed bag. You need to know some facts, to be familiar with some gener concepts, to know a little about how science works and how it comes to conclusions, and know a little about scientists as people. All of these things may affect how you interpret th news of the day. So if you find that the book is something of a potpourri, don't be surprise That's the way science—like everything else in life—is.

Finally, we hope that we can communicate to you another little-known fact about scienc that it is just plain fun—not just "good for you," like some foul-tasting medicine. It grew o of observations of everyday experience by thousands of our ancestors, most of whom actual enjoyed what they were doing. Amid the collection of fact, history, logic, and polic questions that follows, we hope you occasionally catch a glimpse of two people who enjo what they do—who occasionally thrill at the thought of the intellectual beauty of th universe we are privileged to live in and know.

Note on the Second Edition

When we began the first edition of *Science Matters* in 1989 we proposed eighteen great ide of science that we felt framed virtually all discoveries of the natural world and all advanc in technology. We could not have foreseen many of the remarkable developments of the pa two decades—nanotechnology archaea, LEDs, cloning, dark energy, ancient microbial fossi and deep microbial life, evidence for oceans of water on Mars and lakes of methane on Tita ribozymes, carbon nanotubes, extrasolar planets, and so much more. But all of the unanticipated findings fit into the existing framework of science. The core concepts of scien have not changed, and we are unable to point to any fundamentally new scientific princip that has emerged during the 1990s or 2000s. Accordingly, while every chapter has bee significantly updated, we have added only a single new chapter on the explosion of advanc in biotechnology. We conclude that the experience of the past two decades underscores th value of the great ideas approach to achieving scientific literacy.

CHAPTER ONE

Knowing

YOUR LIFE IS FILLED with routine—you set your alarm clock at night, take a shower in th morning, brush your teeth after breakfast, pay your bills on time, and fasten your se belt. With each of these actions and a hundred others every day you acknowledge the pow of predictability. If you don't set the alarm you'll probably be late for work or school. If yo don't take a shower you'll probably smell. If you don't fasten your seat belt and then get in a freeway accident you may die.

We all seek order to deal with life's uncertainties. We look for patterns to help us cop Scientists do the same thing. They constantly examine nature, guided by one overarchi principle:

The universe is regular and predictable.

The universe is not random. The sun comes up every morning, the stars sweep across the sk at night. The universe moves in regular, predictable ways. Human beings can grasp th regularities of the universe and can even uncover the basic, simple laws that produce the We call this activity "science."

WAYS OF KNOWING

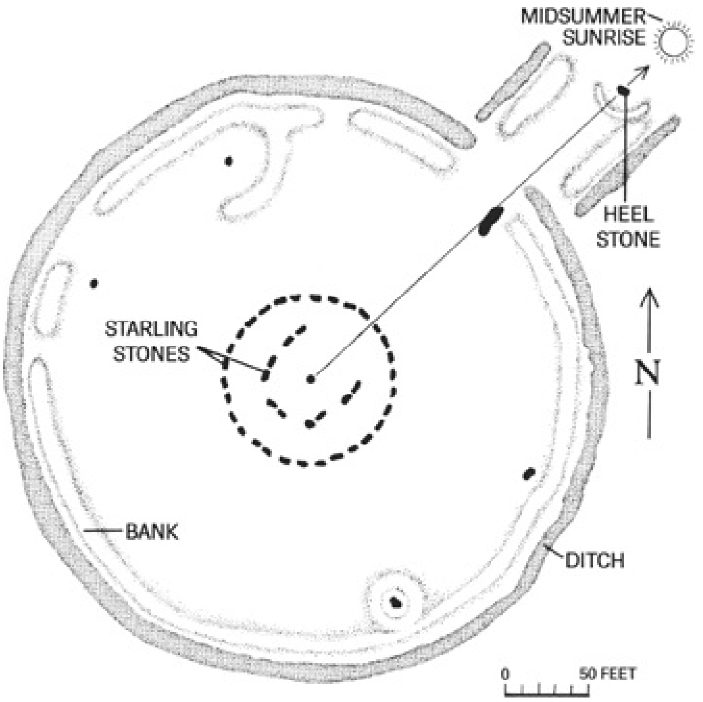
Science is one way of knowing about the world. The unspoken assumption behind th scientific endeavor is that general laws, discoverable by the human mind, exist and gove everything in the physical world. In its most advanced form, science is written in th language of mathematics, and therefore is not always easily accessible to the general publi But, like any other language, the language of science can be translated into simple Englis When this is done, the beauty and simplicity of the great scientific laws can be shared b everyone.

Science is not the only way, nor always the best way, to gain an understanding of th world in which we find ourselves. Religion and philosophy help us come to grips with th meaning of life without the need for experimentation or mathematics, while art, music, an literature provide us with a kind of aesthetic, non-quantitative knowledge. You don't nee calculus to tell you whether a symphony or a poem has meaning for you. Scien complements these other ways of knowing, providing us with insights about a different aspe of the universe.

The Regularity of Nature

Our ancestors perceived the universe in ways that sometimes seem very strange to us. For a but the past few hundred years of human existence the universe was viewed by most peop as a place without deep order or rules, governed by the whims of the gods or even by chanc By noting the daily movements of objects in the sky, however, our ancestors got their fir hints that some kind of order and regularity might exist in nature. The position of the sun, th phases of the moon, and the dominant constellations of stars cycled over the years, decade and centuries with unerring regularity. Whatever governs its motion, the fact is that the su does come up every morning.

Most historians of science point to the need for a reliable calendar to regulate agricultur activity as the impetus for learning about what we now call astronomy. Early astronom provided information about when to plant crops and gave humans their first formal metho of recording the passage of time. Stonehenge, the 4,000-year-old ring of stones in southe Britain, is perhaps the best-known monument to the discovery of regularity and predictabili in the world we inhabit. The great markers of Stonehenge point to the spots on the horizo where the sun rises at the solstices and equinoxes—the dates we still use to mark th beginnings of the seasons. The stones may even have been used to predict eclipses. Th existence of Stonehenge, built by people without writing, bears silent testimony both to th regularity of nature and to the ability of the human mind to see behind immedia appearances and discover deeper meanings in events.



Stonehenge relied on the regular and predictable movements of sun, moon, and stars to serve its builders as a calendar. At the solstices and equinoxes, the light of the sun or moon aligns with the stones, and so documents the passage of time.

The Invention of Science

Astronomy was the first science. Throughout history some of the best minds produced by th human race have pondered the meaning of the celestial display. Most of the resulting theori shared a common property—they all assumed that in some way Earth was special, and th what happened in the heavens had no relevance to phenomena on Earth. In one importa version of the universe, for example, the stars and the planets turned eternally on cryst spheres, and their motion had nothing to do with mundane events like the fall of an apple an orchard. People who believed that the universe was built this way produced a large bo of accurate observations of the positions of heavenly bodies, but astronomers were divorce from craftsmen and artisans who were doing different things for the development of science

While the astronomers were gazing into the heavens, other men and women, equal ingenious, were trying to understand the way things operated on Earth. Their motivation w practical: they studied the properties of heated metals because they wanted to develo stronger alloys, they studied the flow of fluids because they wanted to build canals, the experimented with different combinations of ingredients to make better-tasting food a more effective medicines, and so on. They never seemed to think that the prosaic tasks which they were engaged had anything to do with the stars and planets.

The branch of science that finally broke out and forged a link between the cerebr astronomers and the practical artisans was "mechanics." This is an old term for the study motion. Every system, natural or man-made, contains matter in motion. Planets orbit, bloo circulates, chemicals explode, people walk. Mechanics is the superbly pragmatic science pocket billiards and car crashes, cannonballs and guided missiles. Today, the principles mechanics point to such useful things as stronger buildings, faster cars, more exciting sport and, as always, more sophisticated weapons. But more important from the point of view the birth of modern science, the study of mechanics blazed the trail that subsequent scientis have followed. While studying mechanics, scientists developed and refined the scientif method, a technique that has given us so many new insights into the universe we inhabit.

THE CLOCKWORK UNIVERSE

Modern science can be said to have started with the work of Isaac Newton (1642–1727) England. According to Newton, the universe is something like a clock. In a clock, the extern appearance—the slow sweeping of the hands—is a result of the motion of internal gears. the same way, all of the natural phenomena we see in the world around us are the result of few natural laws working beneath the surface of things. Newton demonstrated that:

One set of laws describes all motion.

For Newton, the key fact about motion was that it occurs in response to the action of one more forces. The "gears" that connect forces and motion are Newton's three laws of motio and they apply to everything that moves. Gases streaming out of an exploding star, a footba thrown downfield, and blood cells in your arteries all move in compliance with these ve simple, but very general, laws.

Uniform Motion and Acceleration

If you’re going to study something like motion, the first thing you have to do is decide wh sorts of motion are found in nature. Scientists recognize only two kinds: uniform ar accelerated. Everything in the universe is either in uniform motion or accelerating.

Any object that stands still or moves in a straight line at constant speed is in unifor motion. A book sitting on your desk, a car driving along an interstate with the cruise contr set at 65 mph, and a spaceship traveling at 1,000 miles per second in deep space are all uniform motion.

Acceleration is any change in motion and occurs when something speeds up, slows dow or changes direction. This definition may seem a little strange, because when you drive a ca “acceleration” means speeding up—not slowing down or turning a corner. Physicists use more general meaning for acceleration—but whatever the definition, it’s something you fe in your gut. Flooring the gas pedal on your car, braking for a light, or rounding a bend a tend to move you around in your seat. And there’s nothing subtle about acceleration—peop don’t ride roller coasters to experience uniform motion.

Newton’s Laws and the Idea of Force

Isaac Newton, building on results from centuries of experiments on moving objects, wro down a compact set of laws that de scribes the nature of all motion. That these laws apply such an immense assortment of situations illustrates the power behind thinking of nature regular and predictable. Newton’s three laws of motion provide a cornerstone of physics ar a model for what a science is supposed to be.

Newton’s laws tell us how to predict the motion of a system just by knowing the forces th act on it. The three laws are stated separately, but they work together like separate gears th run a clock. Like all the fundamental laws that govern science, Newton’s laws of motion ma seem simple—almost simplistic. The deepest insights of the human mind often have th characteristic. Yet, as generations of physics students can testify, there is a subtlety ar richness behind this apparent simplicity—how else could the laws describe everything fro the orbits of Neptune’s moons to the movement of exploding gases in your car’s engine?

The First Law

Every body continues in its state of rest, or of uniform motion in a straight line, unless it is compelled to change that state by forces impressed upon it.

Newton has hidden two important concepts in this intuitively obvious statement. The first inertia—the tendency of objects to continue doing what they’re doing. A rolling ball keeps rolling, a rotating planet keeps on rotating, a stationary book keeps on sitting.

The second concept is force—the thing that compels objects to change their state of motic (i.e., accelerate). Rolling balls can slow down if acted upon by a force. A book will move pushed.

The point of Newton's first law is that changes in motion do not happen spontaneously- there is always a reason for the change. A pencil falls, wind blows, popcorn pops. Yo encounter hundreds of examples every day. If an object accelerates, some kind of force mu be acting. Behind every action verb is a force.

The first law, by itself, says nothing about what forces are, what produces them, or ho many different kinds there might be. Indeed, it took physicists more than two hundred yea after Newton to discover the forces that hold atoms together, and we are still working understand the force that cements the nucleus. Nevertheless, the first law tells us what force does when it acts, and, perhaps more important, it tells us how we can recogni situations in nature in which a force is present.

The Second Law

Force equals mass times acceleration.

Newton's second law defines the exact relationship between an object's bulk, its acceleratio and the forces exerted on it. This is a commonsense sort of law that embodies two intuitive reasonable ideas. First, the second law says the greater the force, the greater the acceleratio The harder a pitcher throws, for example, the faster the ball travels. The more powerful you car engine, the better the pickup.

The second part of the law introduces the concept of mass, which is simply the amount stuff being accelerated. Many of us use the words "mass" and "weight" interchangeabl That's not quite correct, because an object's weight depends on the local force of gravi (things weigh less on the moon), but the mass depends only on how much stuff there is (ho many atoms there are). Again, common sense prevails. Objects with lots of ma (refrigerators, boulders, football linemen) are a lot harder to move than objects with le mass (ice cubes, pebbles, quarterbacks).

The second law is quantitative—it can be written down as an equation ($F = ma$, if yo really want to know). Numbers can be plugged into the equation to find out exactly how fa a spear, cannonball, or spaceship of known mass will travel if it is acted upon by a know force.

In a typical mechanics problem, we know the mass of something (a billiard ball, f example, or a planet) and the force acting on it (the push of a cue stick or gravity). We the use New ton's second law and the branch of mathematics known as calculus to predict ho the thing will move.

Why Newton Would Tell You to Wear a Seat Belt

Imagine yourself driving at 60 miles per hour along the freeway when another car forces yo off the road. What happens if you smash into a tree head-on? Newton's laws of motio provide the answer.

You and the car have considerable inertia, which will be dealt with, one way or anothe by the application of a force. The tree applies a force to the car, stopping it. In the absence a seat belt, however, no force is applied to you, so you keep on moving. You are, in Newton words, "an object in a state of uniform motion," and you will therefore "continue in a state uniform motion unless acted on by a force." The extent of your injuries will be determined b how that force is applied. Without a seat belt the driver and passengers will keep movi until they hit the steering wheel or the windshield.

Seat belts and air bags act to slow you down by applying a smaller force over a long time, and that's a much safer method of applying the stopping force than hitting the steeri wheel or windshield. The total change of motion with or without seat belts and air bags exactly the same, but with modern safety technology the injury-causing force is not nearly great.

The Third Law

To every action force there is an equal and opposite reaction force.

Even though this law is probably the most often quoted of the three, it is the least intuitiv It is obvious that a pitcher exerts a force on the ball, but less obvious that the ball push back on the pitcher's hand with an equal and opposite force. When you stand up, your sho apply a force to Earth just as large as the force Earth's gravity exerts on you. When you try open a screw-top bottle that is stuck, your left hand twists one way while the right hand twisted the opposite way. You cannot touch your lover without feeling his or her touch return.

The third law says that forces always come in equal and opposite pairs, but that the forc in the pairs act on (and therefore accelerate) different objects. You are pushing down on th chair in which you are sitting. The third law says that the chair is exerting an equal upwa force on you. You really can learn Newton's laws by the seat of your pants.

Newton's third law also explains how a rocket can fly in space, even when there's nothi to push against. It works like this: the rocket motor heats gases, which are accelerated o through the engine nozzle. The first law tells us that in order to accelerate gas, we must exe a force on it. That force must, of course, be exerted on the gas by the ship. The third law the tells us that an equal and opposite force must be exerted by the gas on the ship. That's wh makes the ship go. A rocket ship in space is similar to someone standing on roller skates a shooting a gun. Both recoil in one direction as they throw something out in the other.

GRAVITY

Newton's laws tell us what happens when forces act on objects, but the laws tell us nothi about what those forces are. You'll discover several different forces in subsequent chapters- some well understood, like electricity and magnetism, some still mysterious, like the s called strong force. Newton himself described nature's most familiar force—gravity.

Before Newton, there was a kind of schizophrenia evident in the way scientists thoug about gravity. The force that held the planets in their orbits (which we can call celesti gravity) was held to be completely different from the force that makes things fall to th center of the Earth (terrestrial gravity). In the century before Newton, different people ma enormous progress in studying these types of “gravity” separately.

Cannonballs

Terrestrial gravity was an obvious thing to study in an age when cathedrals could collaps and cannonballs could sink ships. What made the work of scientists in the seventeent century different from what had gone before was the appearance, for the first time, o laboratory experiments—controlled studies of gravity’s effect on falling objects. The mo famous of these experiments were performed by the Italian scientist Galileo Galilei (1564 1642). Galileo is best known for his trial on charges of suspicion of heresy for teaching th doctrine that the Earth moves around the sun (instead of vice versa), but in our view his mo revolutionary contribution to science was his demonstration that carefully run experimen can yield profound insights into the nature of the universe. He is, in fact, often called th “father of experimental science.”

Galileo studied terrestrial gravitation not by asking about the nature of gravity, but b *observing* how objects behave when gravity acts on them. In particular, he did a series o experiments on balls rolling down inclined planes (the purpose of the incline being, in h words, to “dilute” gravity enough so that he could measure the time it took for the ball to ro with the primitive clocks available to him). By meticulously measuring the time it took th ball to travel various distances, he was able to find out how the speed of the ball changed transit. His bottom line: Terrestrial gravity causes all objects to accelerate the same amoun regardless of their mass, and the rate of that acceleration is constant. These simp observations allowed Galileo and his contemporaries to understand (and predict) things lik the fall of a stone or the arc of a cannonball. They are the basic facts that tell you everythin you need to know about how unsupported objects behave at the surface of our planet.

Ironically, Galileo probably never performed his most famous “experiment”—dropping tw balls of different masses from the leaning Tower of Pisa to show that all objects fall at th same speed. Had he actually done the experiment, the resistance of the air might have cause the heavier objects to fall slightly faster than lighter ones, thereby disproving the very thes he is famous for establishing!

Planets

While Galileo was working out the effects of terrestrial gravity, European astronomers wer making equally bold progress at understanding movements of the planets. The Germa astronomer Johannes Kepler (1571–1630), using data on planetary motions assembled by th Danish astronomer Tycho Brahe (1546–1601), succeeded in discovering how the plane move in their orbits. He found, for example, that the orbits of all planets (including th earth) are elliptical—not circular, as everyone before had assumed. Like Galileo, h summarized his studies of planetary motion in concise statements, known as Kepler’s laws o planetary motion.

Galileo and Kepler employed a number of similar methods in their research. Both me relied heavily on observational or experimental data. They were not, like many of the colleagues, armchair philosophers. If they wanted to know what the world was like, the actually went out and looked. Both men ended up by summarizing and codifying their resul in a series of statements (or laws) written in mathematical form. These mathematic statements could be used by anyone to make predictions about the real world.

Kepler's laws of planetary motion and Galileo's rules about falling bodies summarized th best scientific knowledge available in astronomy and physics, respectively, but they appeare to have nothing to do with each other. Each referred to a different sphere of reality. It too the genius of Isaac Newton to see that both men were, in fact, studying exactly the sam thing.

The Apple and the Moon

According to Newton, he got his great idea while watching an apple fall in an orchard whi he could see the moon in the sky. He knew the apple fell because a force acted on it (fir law), but it struck him that the force pulling on the apple might well extend all the way o to the moon and pull on that object too. In fact, he knew that since the moon was constant changing direction, a force had to be acting on it. It was this speculation, triggered by simple everyday event, that led to the healing of the artificial distinction between the earth and the heavenly, and that finally gave humanity both a new way to approach the wor (science) and a new metaphor (the clockwork universe).

Newton knew that a dropped apple would fall straight down to Earth under the influenc of terrestrial gravity. Throw an apple straight out and it follows a curved path as gravity pul it down. Throw the apple harder and it lands farther away. Throw it very hard indeed and could even circle Earth. Once it makes one circuit, it will continue around and make anoth (ignoring air resistance), and will in fact continue to do so forever. But of course this is ju what the moon (or any satellite) does. The force that constantly acts on the moon—th keeps pulling it into a curved path instead of the straight line the first law says it shou follow—is gravity, the same gravity that pulls down on the apple. With this insight, Newto abolished the centuries-old split between Earth and the heavens and showed that both we fit subjects for scientific study.

He went even further, deducing the exact mathematical formula for the gravitational forc Only three physical quantities determine gravitational force: the masses of the two objec and the distance between them. He stated his result in what we know as Newton's law universal gravitation:

> *Between any two objects there is an attractive force proportional to the product of the two masses divided by the square of the distance between them.*

This law has many interesting consequences. Obviously any large mass will exert a larg gravitational force, but no special distinction is made between large masses and small one Earth pulls on the apple, but the apple also exerts a force on Earth. In fact, the two forces a the same size. We speak of apples falling to the ground because they are much less massiv than Earth and so undergo a much greater acceleration due to the force exerted by the appl As the apple falls 15 feet to the ground, Earth "falls" a distance about the diameter of a atomic nucleus toward the apple.

The law of gravity tells us that every object in the universe is exerting a gravitational forc on you right now. Earth exerts the biggest, but the person next to you exerts a force as we as do the most distant star and galaxy. In practice, however, the massive sun and nearb moon are the only heavenly bodies that can exert a bigger force on you than familiar nearb objects like buildings. This simple fact is one of several reasons why scientists have a har time taking astrology seriously.

The Clockwork Universe

With the law of universal gravitation, Newton closed the circle on his work. He had the forc —gravity—that operated everywhere, and he had the rules—the laws of motion—th governed the operation of all forces. Suddenly scientists saw the universe in a new wa ordered and predictable as never before. With Newton's equations and the language mathematics, scientists could describe and predict the behavior of all kinds of systems. In th centuries following Newton's work, philosophers compared his vision of the universe to clock. The visible phenomena in the world, like the hands of a clock, move in response to th actions of invisible gears—the natural laws. In the solar system the motions of the planets a governed by the law of universal gravitation and the laws of motion. The planets tick alon as regular as a clock. For the Newtonians, in fact, the universe resembled a clock in oth ways: once set in motion by God, the universe followed an inevitable course. The future wa completely and comfortably predictable.

This is a wonderful vision, but like all scientific ideas it had to be tested. The mo dramatic test of Newton's vision of the universe was made by his fellow Englishman Edmon Halley (1656–1742). Using Newton's laws and historical records, Halley was able to work o the orbit of the comet that now bears his name and to predict its reappearance in the sk When the comet was "recovered" on Christmas Day, 1758, the event powerfully underscore the idea of the clockwork universe. Not only could Newton's scheme explain things that we already known, it could make reliable predictions about events that had yet to occur.

Today, with the advent of quantum mechanics and the field of complex chaotic system scientists' ideas about the clockwork universe have changed. The universe is still, in th modern view, governed by simple laws, but these laws do not always allow us to make th kind of straightforward predictions about the future that Newton envisioned. Neverthele much of the Newtonian mind-set survives in modern science.

THE SCIENTIFIC METHOD

Newton's development of the clockwork universe was the first, classic example of th scientific method in use. The method depends on a constant interplay of observation an theory; observations lead to new theories, which guide more experiments, which help modify the existing theories.

In Newton's case, some of the observations and experiments were recorded by Galile others by Kepler. In each case, the cycle of observation, theory, test-against-new-observatio was repeated until the investigators achieved a complete understanding of the phenomen being studied. Newton, as we pointed out, incorporated these understandings into h sweeping theory of motion, and then his new theory was used to make many predictions lil the projected reappearance of Halley's comet. Only after many such tests was the theor accepted by scientists.

The scientific method does not require researchers to be unbiased observers of natur Scientists almost always have a theory in mind when they perform an experiment. But th method does require that scientists be willing to change their views about nature when th data demand it.

Newton provided a model for the development of modern science in many ways. He wa the first to use the scientific method, and he was the first to show that scientific theories ca develop by incorporation rather than revolution.

When Kepler published his laws of planetary motion, he swept aside the old ideas abo the solar system. This was a revolutionary change—the old notions were seen to be wron and were abandoned. When Newton published his work, however, he showed that all Kepler's laws could be derived from universal gravitation and the laws of motion. His wor then, incorporates Kepler's and expands upon it, but does not invalidate it. In the same wa Newton was able to derive Galileo's conclusions, in corporating them into the sam theoretical framework that ac commodated the description of the planets. This has proved be a common occurrence in science. When Albert Einstein produced the theory of gener relativity, our current best theory of gravitation, it incorporated Newton, Kepler, and Galile and when some future theoretical physicist produces the final unified field theory, it wi likely incorporate Einstein.

Despite what you read in sensationalistic headlines, true revolutions are rare in matu sciences.

SCIENTISTS

The universe seems far too complex to comprehend all at once, so the classic scientif approach is to examine well-defined pieces of our surroundings, one at a time. The univers can be divided into an infinite number of "systems," which are nothing more than parcels matter and energy Each parcel, which can contain almost anything from a single spinni subatomic particle to an entire galaxy, is fair game for scientific study. Astronomers prob stars and the solar system. Chemists investigate systems containing carefully selected grou of atoms. Geologists study minerals or mountain ranges. Biologists examine complex syster called cells or ants or forests. Each system can be something you hold in your hand, like rock, or it can be an integral part of something else, like your body's nervous system.

The scientific enterprise consists of thousands of specialized subdisciplines—the chemist of fluorine, the turtles of Malaysia, the properties of young massive stars, the evolution the AIDS virus, lasers, quarks, diamonds, slime mold—each with its own practitioners a jargon. These varied specialties differ primarily in the size and contents of the system und study. All systems, be they stars, bugs, or atoms, are governed by the same set of natur laws, but they are studied and described in very different ways.

Hundreds of thousands of Americans make their livings as scientists. Most of these wome and men can be described with one of four broad labels: physicist, chemist, geologist, o biologist. Science is a seamless web of knowledge, but people like to create their niches. S each of the four main science branches (not to mention the hundreds of highly specialize "twigs") has developed its own distinctive style and organization.

Physicists study matter and energy, forces and motions—the concepts central to all scienc Physicists take pleasure in pointing out that theirs is the most fundamental science, becau all other fields, from chemistry to cosmology, mineralogy to molecular biology, depend on few basic physical principles. Physicists are the generalists among scientists, and fields as fa apart as molecular biology and field ecology have benefited from an influx of physicists ove the years. Nevertheless, parts of physics have turned into the most abstract of the science Physics conventions are replete with discussions of ten-dimensional space, quarks, and unifie field theories. For some reason many physicists, particularly those in universities, seem t enjoy appearing sloppy and disheveled—always the ones without ties at faculty meetings. you want to make a physicist happy, tell him you thought he was the plumber.

The American Institute of Physics, based in the Washington, DC area, represents abo 100,000 physical scientists, including astronomers, crystallographers, and geophysicists, wh are members of ten affiliated societies. The largest of these groups, the American Physic Society, boasts almost 50,000 hard-core phyicists on its membership rolls. These societie sponsor professional meetings, lobby for physics research and education, and publis prestigious research journals such as *The Physical Review* and *Physics Today*.

Chemists are pragmatists, studying atoms in combinations to discover new and usef chemicals. Most chemists, even those in academia, maintain close ties to industry; science an its applications are seldom far apart. Chemists hold more patents than any other kind o scientist, and they are frequently observed wearing business suits.

The American Chemical Society, headquartered in the nation's capital, represents bot research chemists and chemical engineers. This blend of science and industry, unique amon the major science societies, gives the ACS more than 160,000 members, making it the large U.S. science society (surpassing even the interdisciplinary American Association for th Advancement of Science in total membership). The American Chemical Society sponso meetings, supports chemical education, and publishes numerous books and journals, includin the weekly *Chemical and Engineering News*. As a lobbying organization, the ACS must walk fine line between environmentalists and major chemical corporations, both of whom ar represented among the membership.

Geologists are a different breed. They frequently lecture in worn jeans and sturdy boot seemingly ready to hike miles in the wilderness carrying rocks on their backs. Geolog attracts men and women who love the outdoors and like to get their hands dirty. In practic not all geology is rugged. The earth sciences employ much of the sophisticated lab hardwar of chemistry and physics to decipher the nature and origin of rocks and minerals, oceans an atmospheres.

Most American earth scientists belong to the Washington-based American Geophysic Union, whose 50,000 members encompass a broad range of research, from planetary geolog and physics to meteorology and oceanography. The Geological Society of Americ headquartered in scenic Boulder, Colorado, represents more than 20,000 experimental an field geologists. Both societies are active in international projects because the earth scienc