Secrets of the Universe

RELATIVITY AND QUANTUM MECHANICS

PRINCIPLES OF MODERN PHYSICS

By Paul Fleisher

illustrations by Patricia A. Keeler

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INTRODUCTION

What Is a Natural Law?

Everyone knows what a law is. It's a rule that tells people what they must or must not do. Laws tell us that we shouldn't drive faster than the legal speed limit, that we must not take someone else's property, that we must pay taxes on our income each year.

Where do these laws come from? In the United States and other democratic countries, laws are created by elected representatives. These men and women discuss what ideas they think would be fair and useful. Then they vote to decide which ones will actually become laws.

But there is another kind of law, a scientific law. You probably have heard about Albert Einstein's law of relativity, for example. Among other things, it tells us that nothing in our universe can go faster than the speed of light. Where did that law come from, and what could we do if we decided to change it?

The law of relativity is very different from a traffic speed limit or a law that says you must pay your taxes. Speed limits are different in different places. On many interstate highways drivers can travel 105 kilometers (65 miles) per hour. On crowded city streets they must drive more slowly. But relativity tells us that light travels at exactly the same speed no matter where it is or where it came from. In the country or the city, in France, Brazil, the United States, or even in interstellar space, light travels at 300,000 kilometers per second (186,000 miles per second).

Sometimes people break laws. When the speed limit is 90 kph (55 mph), people often drive 100 kph (60 mph) or even faster. But what happens when you try to break the law of relativity? You can't. Here on Earth, if you accurately measure the speed of light a thousand times, it will always travel at the same rate. It will never be faster or slower.

The law doesn't apply just when people are around, either. It stays in effect whether people are watching or not. The law of relativity is a natural law, or a rule of nature. Scientists and philosophers have studied events in our world for a long time. They have made careful observations and done many experiments. And they have found that certain events happen over and over again in a regular, predictable way. You have probably noticed some of these patterns in our world yourself.

A scientific law is a statement that tells how things work in the universe. It describes the way things are, not the way we want them to be. That means a scientific law is not something that can be changed whenever we choose. We can change the speed limit or the tax rate if we think they're too high or too low. But no matter how much we want to make light go faster or slower, its speed remains the same. We cannot change it; we can only describe it. A scientist's job is to describe the laws of nature as accurately and exactly as possible.

The laws you will read about in this book are universal laws. That means they are true not only here on Earth, but also throughout the universe. The universe includes everything we know to exist: our planet, our solar system, our galaxy, all the other billions of stars and galaxies, and all the vast empty space in between. All the evidence that scientists have gathered about the other planets and stars in our universe tells us that the scientific laws that apply here on Earth also apply everywhere else.

In the history of science, some laws have been found through the brilliant discoveries of a single person. The law of relativity, for example, is the result of Albert Einstein's great flash of individual understanding. But ordinarily, scientific laws are discovered through the efforts of many scientists, each one building on what others did earlier. When one scientist receives credit for discovering a law, it's important to remember that many other people also contributed to that discovery. Even Einstein's discovery was based on problems and questions that many other scientists had been working on for years.

Scientific laws do change, on rare occasions. They don't change because we tell the universe to behave differently. Scientific laws change only if we have new information or more accurate observations. The law changes when scientists make new discoveries that show the old law doesn't describe the universe as well as it should. Whenever scientists agree to a change in the laws of nature, the new law describes events more completely, or more simply and clearly.

Relativity is good example of this. In the 1900s, scientists had believed they should be able to measure differences in the speed of light, depending on whether the light source—a star for example—was moving rapidly toward us or away from us. They kept trying more and more accurate experiments. But better measurements still didn't show any difference. The speed of light always measured the same 300,000 kilometers per second. Einstein finally realized there was nothing wrong with the experiments. Instead, the speed of light was always the same no matter where or when it was measured. This idea meant that scientists had to look at many other laws of the universe in a completely new way that seemed very different from everyday experience.

Natural laws are often written in the language of mathematics. This allows scientists to be more exact in their descriptions of how things work. For example, you've probably heard of Einstein's equation $E=mc^2$.

It's one of the most famous equations in science. But don't let the math fool you. It's simply a mathematical way of saying that mass (m), or matter, can be changed into energy (E). Writing it this way lets scientists compute the amount of energy contained in a certain amount of matter.

The science of matter and energy and how they behave is called physics. In the hundreds of years that physicists have been studying our universe, they have discovered many natural laws. In this book, you'll read about several of these great discoveries. There will be some simple experiments you can do to see the laws in action. Read on, and share the fascinating stories of the laws that reveal the secrets of our universe.

Chapter 1
Relativity

Picture yourself riding down the road in your family's car. The speedometer says you are traveling 80 kilometers (50 miles) per hour. But how fast are you *really* going?

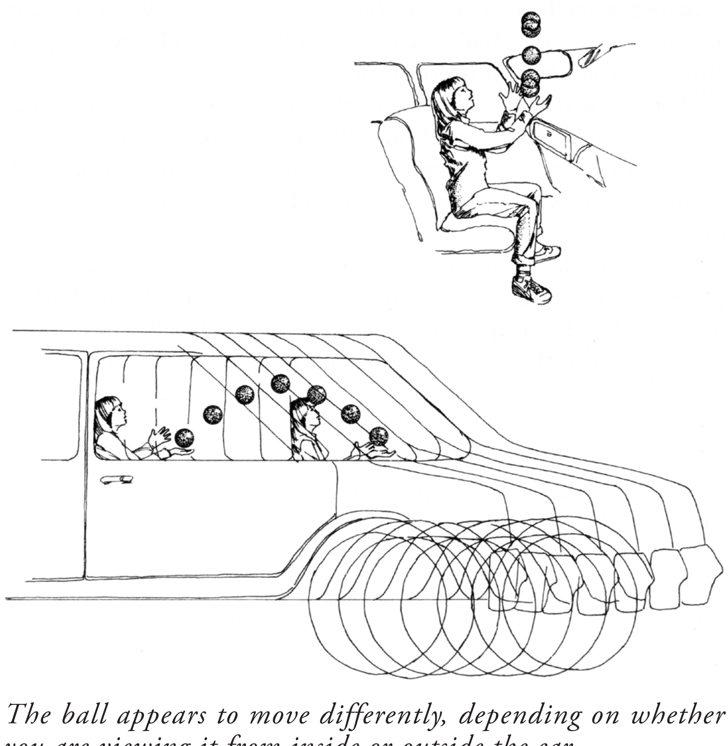
If you look out the window, you'll see the countryside moving past you at 80 kilometers per hour. But look at the person sitting next to you in the car. It looks as if he or she isn't moving at all. You're both sitting perfectly still. Are you really moving or not?

If you think about the situation further, it gets even more puzzling. Your car is traveling on the surface of Earth. Earth is rotating on its axis at about 1,700 kilometers (1,000 miles) per hour, and so is everything on it. Perhaps you are really moving *that* fast.

But wait. Earth is traveling around the Sun at a speed of 30 kilometers (about 20 miles) per second. And the solar system is moving through our galaxy at a speed of about 240 kilometers (150 miles) per second. So, which is the correct speed for your car? The answer is: it depends on what you compare your speed to. You can't measure speed unless you choose something to measure it against. Your car's speedometer measures your speed by comparing it to the road, which it considers to be standing still.

Now suppose you toss a ball up and down as you sit in your car riding down the road. You would see the ball going straight up and down. But someone standing by the roadside would see something completely different. He or she would see the ball moving forward as it goes up and down. Both of you would be correct, from your own points of view. What the ball is *really* doing depends on how it is being seen.

The name for this idea is *relativity*. Relativity means



The ball appears to move differently, depending on whether you are viewing it from inside or outside the car.

that what you observe and measure about an event depends on your own point of view, as well as the event itself. Observations are *relative* to the frame of reference, or viewpoint, of the observer.

Relativity also applies to larger events in the universe. For example, we can tell how fast our planet is moving only if we compare it to something else. Imagine a single planet in a completely empty universe. How fast is it moving? In what direction is it going? Unless we can compare it to some other object, those questions are meaningless.

Around 1900, a young German physicist named Albert Einstein wondered about relativity. How does it affect objects traveling at very high speeds? Light travels *very* fast—300,000 kilometers per second in a vacuum. So Einstein wondered what light waves would look like to a person traveling at the speed of light. He realized one possible answer might be that the light would seem to be standing still, just as the person sitting next to you in the moving car seems to be sitting still.

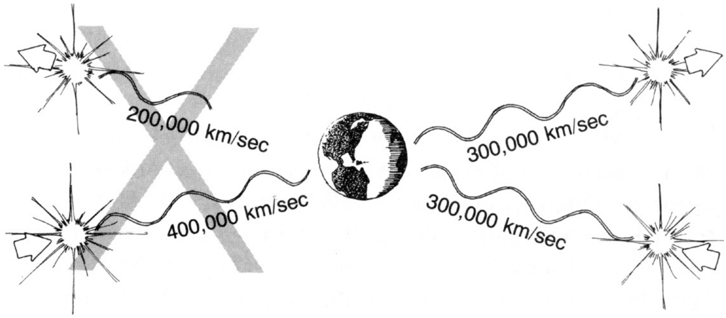
But Einstein knew that answer didn't make sense. Light is made of waves, and waves must *move* to exist. So he decided to explore another possibility. What if the speed of light must *always* measure 300,000 kilometers per second, no matter how fast someone is moving when he or she observes it.

Einstein's law that the speed of light is always constant doesn't seem odd at first. But it doesn't fit our everyday, commonsense view of nature. The velocity (speed of movement in a specific direction) of everything else in our world works by addition and subtraction. For example, imagine you are riding in a car at 50 kilometers (about 30 miles) per hour. You throw an apple core out the window at 10 kilometers (about 6 miles) per hour in the direction you are traveling. The total velocity of the apple core must be 60 kilometers (about 36 miles) per hour. If you throw the core at 10 kph in the opposite direction, its total velocity would be 40 kph (about 24 mph).

Athletes use this principle when they throw a ball. When a center fielder has to make a quick throw to home plate, she runs a couple of steps toward her target before she winds up and releases her throw. That way the ball has the velocity from her throwing arm *plus* the extra velocity of her running speed as she lets the ball go.

Imagine two stars, one moving toward Earth at 100,000 kilometers (60,000 miles) per second and one moving away at the same rate. Both stars are producing light that travels 300,000 kilometers per second. If light acted like other things in our everyday world, we would expect the light from the first star to move toward us at 400,000 kilometers (about 250,000 miles) per second while the light from the other would move toward us at 200,000 kilometers (about 120,000 miles) per second. That would seem perfectly sensible.

The trouble is, that's not what happens. Scientists in the 1800s and early 1900s tried many times to measure differences in the speed of light resulting from the motion of Earth and the stars. The most famous of these experiments was conducted by Albert Michelson and



The speed of light is always the same, no matter how fast the source of the light may be moving either toward or away from us.

Edward Morley. No matter how carefully scientists designed and carried out their experiments, light always traveled at 300,000 kilometers per second. It was one of the great scientific puzzles of the time.

Most physicists thought the experiments must not have been designed correctly, or that the instruments used to make the measurements weren't accurate enough. But Einstein realized the experiments had been right all along. The experimenters couldn't measure any differences in the speed of light because light always travels at the same rate. Einstein understood this must be a basic rule of the universe.

The universal speed of light seems fairly simple. But Einstein saw that if light always travels at a constant speed, many other rules of the universe that were considered common sense would have to change. Relativity predicts results that seem strange and very different from our everyday experiences. The mathematical calculations that explained these odd realities to Einstein are difficult. But every one of Einstein's predictions has been proven true since his work was first published in 1905.

One of the most interesting results of Einstein's law is called time dilation. That means time, as viewed by an outside observer, slows down as an object moves faster. Imagine a spaceship zooming past Earth at 200,000 kilometers per second. If we on Earth could somehow see the clocks on that ship, they would seem to be moving much too slowly. Even stranger, imagine the people on the spaceship could see Earth at the same time. They would see our planet flashing by at 200,000 kilometers per second. Everything on their ship would seem perfectly normal to them. But from their point of view, clocks on Earth would also seem too slow!

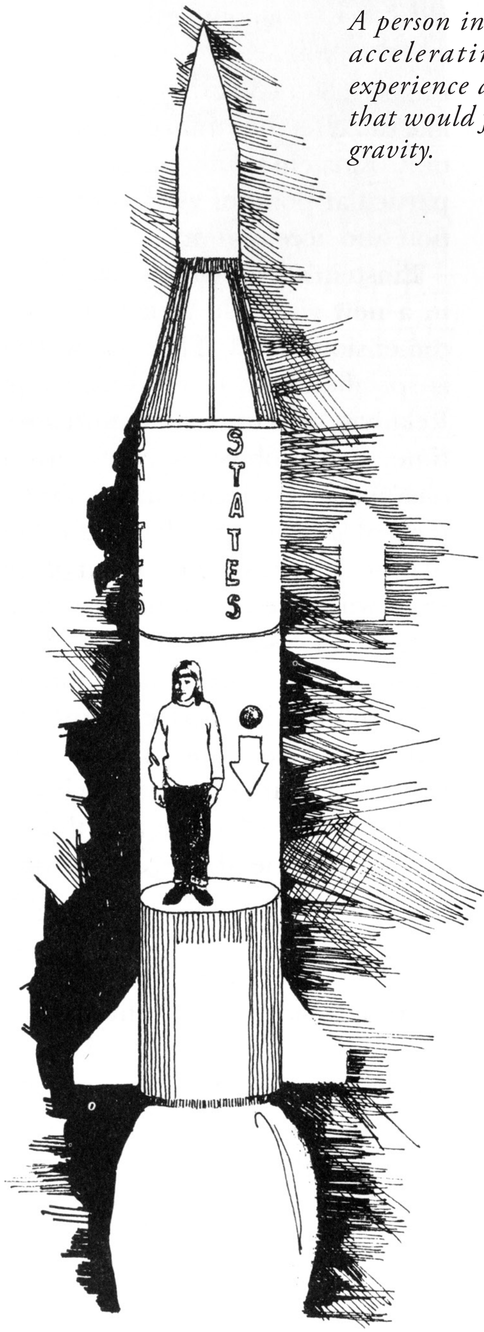
This strange stretching out, or *dilation*, of time has actually been observed in experiments. Usually the tiny subatomic particles called muons exist for only two-millionths of a second before they disintegrate. But when they are moving near the speed of light, they last much longer. Their time is stretched out because of their speed.

Another very important part of Einstein's discovery was that energy and mass (matter) are interchangeable. Mass can be changed into energy, and energy can become matter. Relativity tells us that when an object is accelerated closer and closer to the speed of light, it gains more and more mass. This has also been seen in experiments. Physicists give atomic particles—like protons or electrons—huge boosts of speed in giant particle accelerators, or *atom smashers*. As these particles approach the speed of light, they actually gain more mass.

This gain in mass means that space travel at the speed of light is not possible. A scientific law discovered in the 1600s by Sir Isaac Newton, Newton's second law of motion, says that the more mass an object has, the more force is needed to accelerate it. If an object such as a spaceship gains more mass as it gets closer to the speed of light, then it will require more and more force to accelerate further. An object moving at the speed of light would have an infinite (limitless) amount of mass. So it would require an infinite amount of force to continue to accelerate. Of course, no engine can produce infinite force. So space travelers will always have to be satisfied with slower-than-light travel.

Mass can also be changed into energy. That is exactly what happens in a nuclear reactor or a nuclear bomb. A small amount of uranium or plutonium metal is converted into energy, mostly heat and light. If this event is controlled, the heat can be used to generate electricity. If it happens all at once, it creates a huge explosion.

The part of Einstein's law that tells us the speed of light is constant for any observer is known as *special relativity*. That's because it deals with the special case of constant, unaccelerated motion. In 1916, Einstein published another portion of his laws of relativity, known as *general relativity*. This part of Einstein's laws gives a new and better explanation for the force of gravity. General relativity tells us there is no difference between gravity and acceleration. At least, there is no difference we can see, feel, or measure.



A person in an enclosed, smoothly accelerating spaceship would experience a "downward" pressure that would feel just like the Earth's gravity.