ural 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 or more forces. The "gears" that connect forces and motion are Newton's three laws of motion, and they apply to everything that moves. Gases streaming out of an exploding star, a football thrown downfield, and blood cells in your arteries all move in compliance with these very simple, but very general, laws.

Reading 3 Intro Motion

MOTION

(Constant)

Uniform Motion and Acceleration

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

constant

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

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

Motion G.O.

Newton's Laws and the Idea of Force

Rdg 4a Force & Newton's Laws

Isaac Newton, building on results from centuries of experiments on moving objects, wrote down a compact set of laws that describes the nature of all motion. That these laws apply to such an immense assortment of situations illustrates the power behind thinking of nature as regular and predictable. Newton's three laws of motion provide a cornerstone of physics and 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 that act on it. The three laws are stated separately, but they work together like separate gears that run a clock. Like all the fundamental laws that govern science, Newton's laws of motion may seem simple—almost simplistic. The deepest insights of the human mind often have this characteristic. Yet, as generations of physics students can testify, there is a subtlety and richness behind this apparent simplicity—how else could the laws describe everything from the orbits of Neptune's moons to the movement of exploding gases in your car's engine?

The First Law Changes in motion require a force

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 is inertia—the tendency of objects to continue doing what they're doing. A rolling ball keeps on 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 motion (i.e., accelerate). Rolling balls can slow down if acted upon by a force. A book will move if 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. You encounter hundreds of examples every day. If an object accelerates, some kind of force must be acting. Behind every action verb is a force.

The first law, by itself, says nothing about what forces are, what produces them, or how many different kinds there might be. Indeed, it took physicists more than two hundred years after Newton to discover the forces that hold atoms together, and we are still working to understand the force that cements the nucleus. Nevertheless, the first law tells us what a force does when it acts, and, perhaps more important, it tells us how we can recognize 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 acceleration, and the forces exerted on it. This is a commonsense sort of law that embodies two intuitively reasonable ideas. First, the second law says the greater the force, the greater the acceleration. The harder a pitcher throws, for example, the faster the ball travels. The more powerful your car engine, the better the pickup.

The second part of the law introduces the concept of mass,

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

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

In a typical mechanics problem, we know the mass of something (a billiard ball, for example, or a planet) and the force acting on it (the push of a cue stick or gravity). We then use Newton's second law and the branch of mathematics known as calculus to predict how 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 you off the road. What happens if you smash into a tree head-on? Newton's laws of motion provide the answer.

You and the car have considerable inertia, which will be dealt with, one way or another, by the application of a force. The tree applies a force to the car, stopping it. In the absence of a seat belt, however, no force is applied to you, so you keep on moving. You are, in Newton's words, "an object in a state of uniform motion," and you will therefore "continue in a state of uniform motion unless acted on by a force." The extent of your injuries will be determined by how that force is applied. Without a seat belt the driver and passengers will keep moving 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 longer time, and that's a much safer method of applying the stopping force than hitting the steering wheel or windshield. The total change of motion with or without seat belts and air bags is exactly the same, but with modern safety technology the injury-causing force is not nearly so 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 intuitive. It is obvious that a pitcher exerts a force on the ball, but less obvious that the ball pushes back on the pitcher's hand with an equal and opposite force. When you stand up, your shoes apply a force to Earth just as large as the force Earth's gravity exerts on you. When you try to open a screw-top bottle that is stuck, your left hand twists one way while the right hand is twisted the opposite way. You cannot touch your lover without feeling his or her touch in return.

The third law says that forces always come in equal and opposite pairs, but that the forces in the pairs act on (and therefore accelerate) different objects. You are pushing down on the chair in which you are sitting. The third law says that the chair is exerting an equal upward 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 nothing to push against. It works like this: the rocket motor heats gases, which are accelerated out through the engine nozzle. The first law tells us that in order to accelerate gas, we must exert a force on it. That force must, of course, be exerted on the gas by the ship. The third law then tells us that an equal and opposite force must be exerted by the gas on the ship. That's what makes the ship go. A rocket ship in space is similar to someone standing on roller skates and shooting a gun. Both recoil in one direction as they throw something out in the other.

Rdg 5
Gravity
+p16 exert

GRAVITY

Newton's laws tell us what happens when forces act on objects, but the laws tell us nothing 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 so-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 thought about gravity. The force that held the planets in their orbits (which we can call celestial gravity) was held to be completely different from the force that makes things fall to the center of the Earth (terrestrial gravity). In the century before Newton, different people made enormous progress in studying these types of "gravity" separately.

Galileo [illegible]
[illegible]
Rdg 6

Cannonballs

Terrestrial gravity was an obvious thing to study in an age when cathedrals could collapse and cannonballs could sink ships.

What made the work of scientists in the seventeenth century different from what had gone before was the appearance, for the first time, of laboratory experiments—controlled studies of gravity's effect on falling objects. The most 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 the doctrine that the Earth moves around the sun (instead of vice versa), but in our view his most revolutionary contribution to science was his demonstration that carefully run experiments can yield profound insights into the nature of the universe. He is, in fact, often called the "father of experimental science."

Galileo studied terrestrial gravitation not by asking about the nature of gravity, but by *observing* how objects behave when gravity acts on them. In particular, he did a series of experiments on balls rolling down inclined planes (the purpose of the incline being, in his words, to "dilute" gravity enough so that he could measure the time it took for the ball to roll with the primitive clocks available to him). By meticulously measuring the time it took the ball to travel various distances, he was able to find out how the speed of the ball changed in transit. His bottom line: Terrestrial gravity causes all objects to accelerate the same amount, regardless of their mass, and the rate of that acceleration is constant. These simple observations allowed Galileo and his contemporaries to understand (and predict) things like the fall of a stone or the arc of a cannonball. They are the basic facts that tell you everything 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 two balls of different masses from the leaning Tower of Pisa to show that all objects fall at the same speed. Had he actually done the experiment, the resistance of the air might have caused the heavier objects to fall slightly faster than lighter ones, thereby disproving the very thesis he is famous for establishing!

Planets

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

Galileo and Kepler employed a number of similar methods in their research. Both men relied heavily on observational or experimental data. They were not, like many of their colleagues, armchair philosophers. If they wanted to know what the world was like, they actually went out and looked. Both men ended up by summarizing and codifying their results in a series of statements (or laws) written in mathematical form. These mathematical 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 the best scientific knowledge available in astronomy and physics, respectively, but they appeared to have nothing to do with each other. Each referred to a different sphere of reality. It took the genius of Isaac Newton to see that both men were, in fact, studying exactly the same thing.

The Apple and the Moon

Read

Read w/ gravity p13

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

orbit rdg + tho
w/ diagram

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

He went even further, deducing the exact mathematical formula for the gravitational force. Only three physical quantities

determine gravitational force: the masses of the two objects and the distance between them. He stated his result in what we know as Newton's law of 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 large gravitational force, but no special distinction is made between large masses and small ones. Earth pulls on the apple, but the apple also exerts a force on Earth. In fact, the two forces are the same size. We speak of apples falling to the ground because they are much less massive than Earth and so undergo a much greater acceleration due to the force exerted by the apple. As the apple falls 15 feet to the ground, Earth "falls" a distance about the diameter of an atomic nucleus toward the apple.

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

Stop

The Clockwork Universe

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

This is a wonderful vision, but like all scientific ideas it had to be tested. The most dramatic test of Newton's vision of the universe was made by his fellow Englishman Edmond Halley (1656–1742). Using Newton's laws and historical records, Halley was able to work out the orbit of the comet that now bears his name and to predict its reappearance in the sky. When the comet was "recovered" on Christmas Day, 1758, the event powerfully underscored the idea of the clockwork universe. Not only could Newton's scheme explain things that were 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 systems, scientists' ideas about the clockwork universe have changed. The universe is still, in the modern view, governed by simple laws, but these laws do not always allow us to make the kind of straightforward predictions about the future that Newton envisioned. Nevertheless, 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 the scientific method in use. The method depends on a constant interplay of observation and theory; observations lead to new theories, which guide more experiments, which help to modify the existing theories.

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

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

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

When Kepler published his laws of planetary motion, he swept aside the old ideas about the solar system. This was a revolutionary change—the old notions were seen to be wrong and were abandoned. When Newton published his work, however, he showed that all of Kepler's laws could be derived from universal gravitation and the laws of motion. His work, then, incorporates