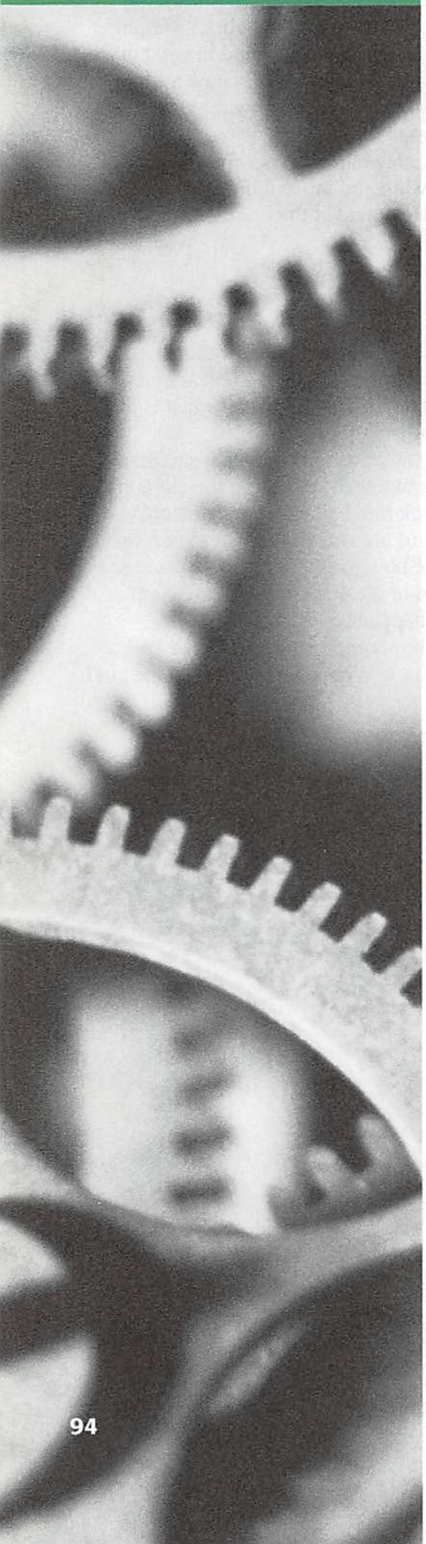
CHAPTER

5

Newton's Universe



And from my pillow, looking forth by light
Of moon or favouring stars, I could behold
The antechapel where the statue stood
Of Newton with his prism and silent face,
The marble index of a mind for ever
Voyaging through strange seas of Thought, alone.

William Wordsworth. *Prelude* (Book III), 1850

The law of inertia might be history's most fruitful scientific idea. Besides unifying natural motion on Earth and in the heavens, undermining Aristotelian views, promoting the idea of universal natural law, and leading to Newton's law of motion, it also led Newton to look in a new way at one specific kind of force: gravity.

Because gravity is all around us all the time, it's difficult to even notice it. This has made it difficult for scientists to properly conceptualize it. From Aristotle until Newton, people believed that every solid body had a natural tendency to seek out Earth's center, in the way that a thirsty person seeks out water. External influences—forces—were not needed to explain why objects fell: They fell because they "wanted" to. But the inertial view is that bodies "want" to maintain their velocity. Descartes first conceived of this new view of motion. It was a conceptual shift comparable to Copernicus's shift to a sun-centered view.

Newton then built on Descartes's idea. If you believe that bodies have inertia, you must ask why an apple, released above the ground, falls. Newton's answer applied to more than apples; it demonstrated that the same gravitational forces are at work in the heavens as on Earth. We live in one universe, not two.

Section 5.1 presents the general idea of Newton's theory of gravity, and Section 5.2 gives the specifics along with examples. One significant social/cultural development of the past 100 years is our increased scientific understanding of the origin and future of our universe, our planet, life, and humans. I'll delve into such topics at several points in this book, beginning with Sections 5.3 and 5.4. Section 5.3 applies Newton's theory of gravity to the birth and death of the sun and Earth. Section 5.4 tells of the violent gravitational collapse of stars that are more massive than the sun and the exotic objects that result from the collapse. Sections 5.5 and 5.6 return to our theme of comparing Newtonian and modern physics: Section 5.5 looks at broad implications of Newtonian physics, particularly the "mechanical universe." Section 5.6 notes the limitations of Newtonian physics in light of modern physics.

5. What would a skydiver's acceleration be if air resistance were half as large as the skydiver's weight? What if air resistance were as large as the skydiver's weight?
6. How much force must a pitcher exert on a 0.5 kg baseball in order to accelerate it at 50 m/s^2?
7. Find the force acting on a 0.01 kg bullet as it is accelerated at 1 million m/s^2 (100,000 times larger than the acceleration due to gravity!) down a rifle barrel.
8. A 2 kg flower pot weighing 20 N falls from a window ledge. How large must air resistance be in order that the pot fall with an acceleration of 8 m/s^2?
9. An 80 kg firefighter whose weight is 800 N slides down a vertical pole with an acceleration of 3 m/s^2. What is the frictional force on the firefighter?
10. A black box and a white box accelerate at the same rate across the floor despite the fact that the net force on the black box is four times larger than the net force on the white box. Which box has the larger mass, and how much larger?
11. A 70 kg runner speeds up from 6 m/s to 7 m/s in 2 s. Find the runner's acceleration and the frictional force by the ground on the runner during this time.
12. A 1 tonne (1000 kg) automobile experiences 100 N of air resistance and 200 N of rolling resistance. How large a forward force must the road exert on the drive wheels in order for the automobile to accelerate at 0.5 m/s^2?

THE LAW OF FORCE PAIRS

13. Wearing frictionless roller skates, you push horizontally against a wall with a force of 50 N. How hard does the wall push on you?
14. In Problem 13, if your mass is 40 kg, then what is your acceleration?
15. Your friend (mass 80 kg) and you (mass 40 kg) are both wearing frictionless roller skates. You are at rest, behind your friend. You push on your friend's back with a force of 60 N. How hard does your friend's back push on you?
16. In the preceding question, what is your acceleration? What is your friend's acceleration?
17. A small car having a mass of 1000 kg runs into an initially stationary 60,000 kg 18-wheeled truck from behind, exerting a force of 30,000 N on the truck. How big, and in what direction, is the force that the truck exerts on the car?
18. In the preceding question, find the car's acceleration. Is this a "speeding up" or a "slowing down" type of acceleration? Find the truck's acceleration. Is this of the "speeding up" or "slowing down" variety?
19. You press downward with a 100 N force on a brick weighing 40 N that rests on a table. With what force, and in what direction, does the brick press against your hand? Draw a force diagram similar to Figure 4.16, with an arrow representing each force acting on the brick.
20. In the preceding question, how big is the net force on the brick? Find the force (how big and in what direction) that the table exerts on the brick. How hard is the brick pressing down against the table?

MOMENTUM

21. A 1000 kg car moving at 20 m/s slams into a stationary 27,000 kg truck from the rear, and sticks to the rear end of the truck. Assuming the truck is free to roll, how fast is the wreck moving after the collision?
22. A 27,000 kg truck moving at 20 m/s slams into a stationary 1000 kg car. The two stick together. Assuming the car is free to roll, how fast is the wreck moving after the collision?
23. A 50 kg boy and a 30 kg girl are standing on ice skates on a smoothly frozen pond. The boy gives the girl a push and she slides at unchanging speed to the edge of the pond, 20 m away, in 4 seconds. What happens to the boy?
24. A 30 kg girl standing on slippery ice catches a 0.5 kg ball thrown with a speed of 16 m/s. What then happens to the girl?

5.1 THE IDEA OF GRAVITY: THE APPLE AND THE MOON

One has to be a Newton to see that the moon is falling, when everyone sees that it doesn't fall.

Paul Valery, French Poet and Philosopher, 1871–1945

Isaac Newton, age 22, had just completed his bachelor of arts degree at Cambridge University in England. He was invited to remain, but the school then closed for 18 months because of a plague epidemic, so the graduate returned to his family's farm. But he didn't just snooze. During those 18 months, Newton laid the foundations for a theory of gravity and a theory of light and, in his spare time, invented calculus.

Some say that greatness is partly a matter of timing. Newton lived at a time that was culturally ripe for a new view of the universe. The scientific foundations had been laid by Copernicus, Brahe, Kepler, Galileo, and Descartes. You have seen that the inertial view of Descartes and Galileo leads naturally to Newton's law of motion. The concepts surrounding the law of motion, plus the astronomy of Copernicus and Kepler, then led Newton to the law of gravity. Newton stood, as he himself said, "on the shoulders of giants."

As Newton recounted it late in life, the central idea of his theory of gravity came to him during his stay on the family farm when an apple fell from a tree while he could see the moon in the sky. Beyond the fact that both are more or less round, it's difficult to think of two more dissimilar objects than an apple and the moon. One is on Earth, the other in the heavens; one rots, the other seems eternal; one falls to the ground, the other remains aloft. Yet where others saw difference, Newton saw resemblance.

Let's trace Newton's thinking. **Figure 5.1** shows an apple falling toward the ground, accelerated by Earth's gravitational pull. The directions of the apple's velocity, acceleration, and gravitational force are all downward toward Earth's center, as shown. The moon's motion is quite different. The direction of its velocity is parallel to Earth's surface rather than toward its center. But we are interested in the forces on each, and, according to the inertial view, forces cause accelerations, not velocities. So the forces on the two could be similar, despite the dissimilarity of the velocities. How do the forces compare?

Aristotle would say that no force is needed to make the moon move in a circle because that is its natural motion, but the inertial view is that in order for the moon to deviate from straight-line motion, a force must act on it. What is the direction of

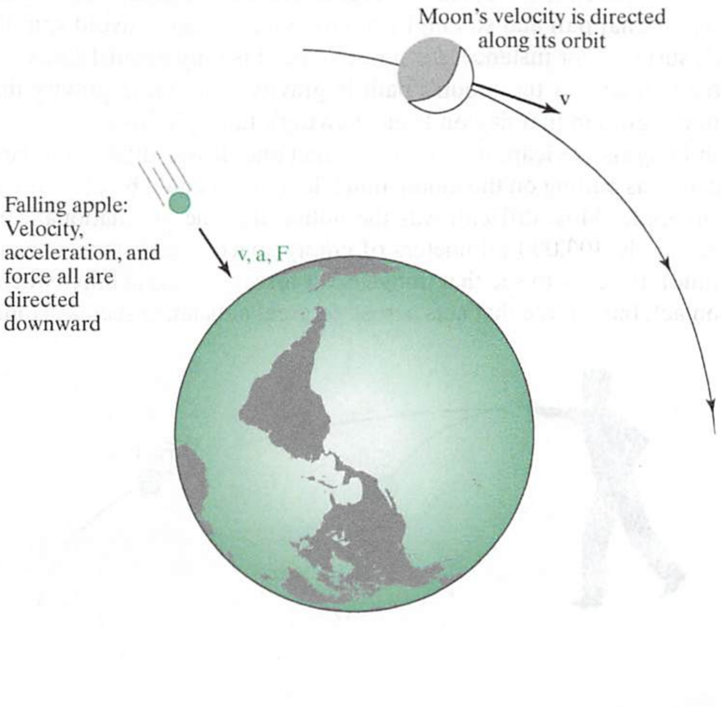


Figure 5.1
The apple and the moon.

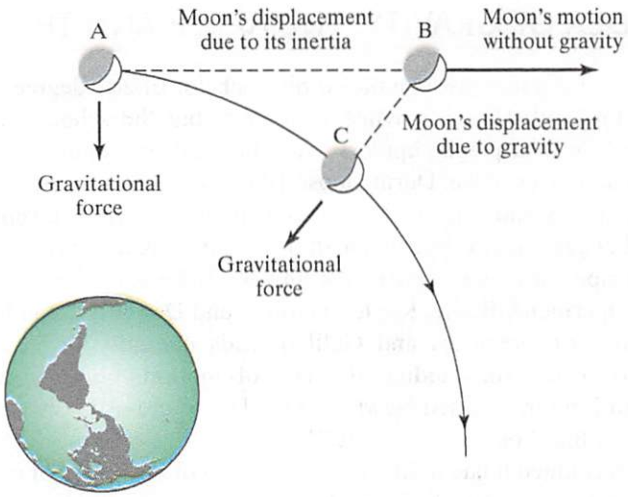


Figure 5.2
The moon is held into its orbit by an inward-directed force.

this force? If the moon were at point A in **Figure 5.2** and if no force acted on it, it would move in a straight line toward point B. But instead it moves around to point C. As you can see from Figure 5.2, the force required to pull the moon inward—so that it arrives at C rather than B—is directed *toward Earth's center,* just like the force on a falling apple. Newton hypothesized that this force has the same source as the force that pulls an apple downward: Earth's gravitational attraction.

Newton offered another argument, one that helps us understand why the moon and other satellites stay up. If you throw an apple horizontally, it will follow a curved path as it falls to the ground (**Figure 5.3**). If you throw the apple faster, it will go farther before hitting the ground. And if you throw it fast enough, it might "fall" around a large part of Earth's surface before striking the ground (**Figure 5.4**). If the apple is launched at such a high speed that the curvature of its path just matches Earth's curvature, it will fall all the way around. In other words, it goes into orbit. The required speed is about 8 km/s, or 29,000 km/hr. This is what any orbiting satellite does, except that the required speed is less for higher-altitude satellites because they feel a smaller gravitational pull and so don't need to move as fast to avoid spiraling down onto Earth's surface. For instance, the moon's speed is only about 1 km/s.

The force that shapes the moon's path is gravity—the same gravity that pulled the apple to the ground that day on Isaac Newton's family's farm.

It was an imaginative leap, in more ways than one. It was difficult to believe that anything at all was pulling on the moon, much less that it could be the same force that pulled on an apple. Most difficult was the notion that the gravitational force could reach across nearly 400,000 kilometers of empty space (the distance was known in Newton's time). It's easy to see that things exert forces on one another when they are in direct contact, but a force that acts across so great a distance seems astonishing.

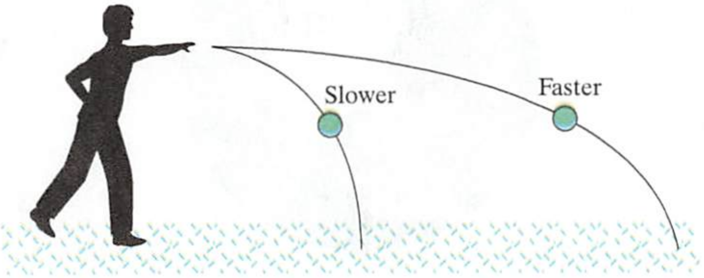


Figure 5.3
If you throw an apple horizontally, the faster you throw it, the farther it will go.

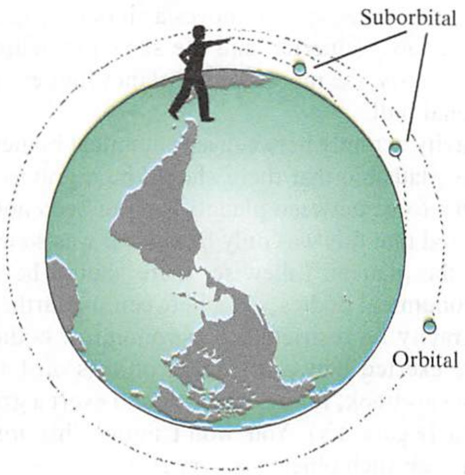


Figure 5.4
Falling around Earth. If you throw an apple fast enough, it will fall around a large part of Earth's surface or even go into orbit. A diagram like this appears in Newton's notebook.

CONCEPT CHECK 1 A 2 N apple falls from a tree. Neglecting air resistance, while it is freely falling the net force on it is (a) zero; (b) 2 N downward; (c) 2 N upward.

CONCEPT CHECK 2 In the preceding question, the apple's acceleration is (a) zero; (b) impossible to determine from the given information; (c) about 10 m/s^2 downward; (d) about 10 m/s^2 upward.

CONCEPT CHECK 3 Suppose you throw a 2 N apple horizontally, as shown in Figures 5.3 and 5.4. Neglecting air resistance, the net force on the apple when it is in the five positions shown is (a) zero; (b) 2 N in the forward direction (along the direction of motion); (c) 2 N downward (toward Earth's center); (d) 2 N upward (away from Earth's center); (e) impossible to determine.

CONCEPT CHECK 4 The net forces in Concept Checks 1 and 3 are the same in both magnitude and direction. So, what must be the numerical value and direction of the apple's acceleration in Figures 5.3 and 5.4? (a) Zero. (b) Impossible to determine from the given information. (c) About 10 m/s^2 in the forward direction. (d) About 10 m/s^2 downward. (e) About 10 m/s^2 upward.

5.2 NEWTON'S THEORY[1] OF GRAVITY: MOVING THE FARTHEST STAR

Since Earth's gravitational pull holds the moon into its orbit, it's reasonable to suppose that all **satellites**—bodies in orbit around larger astronomical bodies—are held in their orbits by the gravitational pull exerted by the larger body. Since the planets are satellites of the sun, Newton's insight regarding the moon also resolves

What makes planets go around the sun? At the time of Kepler some people answered this problem by saying that there were angels behind them beating their wings and pushing the planets around an orbit.... The answer is not far from the truth. The only difference is that the angels sit in a different direction and their wings push inwards.

Richard Feynman, Physicist

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[1] This theory is usually called Newton's *law* of gravity. But the term *law*, which is always inappropriate in science because every general scientific principle is subject to some doubt (see Chapter 1), is especially inappropriate here. The reason is that Newton's theory of gravity has limitations, beyond which the theory isn't valid. The more accurate theory, having no known limitations, is always called Einstein's *theory* of general relativity (Chapter 11). It's ridiculous to call Newton's theory a "law" while calling Einstein's theory a "theory."

> Pick a flower on Earth and you move the farthest star!
>
> Paul Dirac, Physicist

the old question of why the solar system moves as it does! The planets keep moving forward because of the law of inertia, and the sun's gravitational pull bends their orbits into ellipses. Similarly, the moons of the planet Jupiter are held in their orbits by Jupiter's gravitational pull.

But why would gravity act only between astronomical bodies and their satellites? For instance, it seems plausible that there should be a gravitational force between Earth and Mars. Such a force between planets had not been noticed yet in Newton's day, but Newton realized that this was only because it was so much smaller than the force by the sun on the planets. Likewise, there should be a gravitational force between any two astronomical bodies, even between the farthest stars.

But why should gravity be restricted to astronomical bodies? Why shouldn't a gravitational force be exerted between smaller objects on Earth—oranges, rocks, and so forth? Your physics book, for instance, should exert a gravitational pull on an apple, and vice versa (**Figure 5.5**). You won't notice this force, but that is only because the force between such objects is very small.

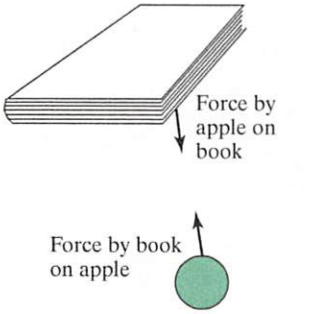


Figure 5.5
Even ordinary-sized objects exert gravitational forces on one another. Your physics book exerts a force on an apple, and vice versa. It's a small force, but forces like this have been measured.

So Newton reasoned that the gravitational force is universal; it's exerted between every pair of objects throughout the universe. This is the central idea of Newton's theory of gravity.

Newton understood the importance of quantitative methods. Although his basic insight was qualitative, its expression in a quantitative form led to powerful explanations and predictions. Quantitatively, the gravitational attraction between two objects must be stronger when the objects' masses are larger, because an apple's weight is larger when its mass is larger (double the mass, for example, by replacing the one apple by two apples glued together, and you double the weight). And since widely separated objects attract each other only weakly, the gravitational force should get smaller when the distance between the objects gets larger.

Newton put all this together (see "How Do We Know Newton's Theory of Gravity?" later in this section) and came to the following conclusions:

Newton's Theory of Gravity

Between any two objects there is an attractive force that is proportional to the product of the two objects' masses and proportional to the inverse of the square of the distance between them:

$$\text{gravitational force} \propto \frac{(\text{mass of 1st object}) \times (\text{mass of 2nd object})}{\text{square of distance between them}}$$

$$F \propto \frac{m_1 \times m_2}{d^2}$$

If mass is expressed in kilograms, distance in meters, and force in newtons, this proportionality becomes

$$F = 6.7 \times 10^{-11} \frac{m_1 \times m_2}{d^2}$$

For our first example, let's consider your weight—the gravitational force exerted by Earth on you. Newton's theory of gravity tells us that this force is proportional to your mass times Earth's mass, which means that the force is proportional to each of the two masses separately. So doubling your mass would double your weight, tripling your mass would triple your weight, and so forth—which certainly makes sense. But the theory also says that if you imagined that somehow Earth's mass were doubled (without, however, changing its size), this also would double your weight; halving Earth's mass would halve your weight; and so forth. You can reduce your weight without dieting or exercising: Simply reduce Earth's mass! What if you altered both masses? For instance, suppose you tripled your mass while simultaneously doubling Earth's mass. Since the force is proportional to the product of the two masses, this would multiply your weight by 6.

What happens when the distance between Earth and you is changed? In fact, exactly what is meant by the "distance between the objects" in a case like this? Does the distance from Earth to your body mean the distance from the near side of Earth (the ground beneath your feet), from the far side, from the center, or from some other point? And to what point in your body should you measure the distance? Newton worked through a lot of mathematics to answer this—in fact, he invented "integral calculus" to answer it. Newton's answer was that the distance between the "centers" of the two bodies is the correct distance to use when applying the gravitational force formula to two extended bodies. In the case of a body such as Earth that has an obvious center, distance is measured from that center. For other bodies, such as your own, the distance should be measured from the body's "balance point"—the point at which the body would be balanced under the force of gravity. But because your body is so small compared with the distance from Earth's center to your body, it matters little which point you choose within your body.

Suppose you travel away from Earth. Since the gravitational force is proportional to the inverse of the square of the distance, the increased distance makes the force decrease—another way to reduce your weight! For instance, your weight at the top of Mount Everest, nearly 10 km above sea level, is 0.3% less than at sea level. If your weight is normally 600 N (135 lb), it will be 598 N (134.5 lb) at the top of Mount Everest. Your weight reduction is greater at an altitude of a few hundred kilometers, where low-orbit artificial satellites travel. For example, at a 200 km altitude, your weight would be reduced by 6%, so a person normally weighing 600 N would weigh only 560 N. Now you're really losing weight (but unfortunately you're not losing any mass).

Moving to still higher altitudes, suppose you are 6400 km—1 Earth radius—above the ground. What is your weight? The proportionalities in the theory of gravity make this an easy question. If you rise 1 Earth radius above the ground, your distance from Earth's center doubles, so the square of the distance quadruples. Since the force is proportional to the inverse of the square of the distance, the force is divided by 4. Your weight is now one-fourth of normal. **Figure 5.6** is a graph of your weight at various distances from Earth's center. No matter how far you are from Earth, the gravitational force by Earth on your body never reaches precisely zero. But very far away, the force becomes very small. For example, at 10 Earth radii, your weight is 1% of your normal weight.

It's a good thing for us that the force of gravity declines at larger distances in just the way it does. If the gravitational force declined a little faster, the planets would not move in ellipses but would instead spiral into the sun, and you would not be here to ask about things like gravity. And if the gravitational force declined a little more slowly, the gravity from distant stars would dominate the gravity from Earth, and again you would not be here. It's something to think about.

You can use the theory of gravity to calculate the gravitational attraction between any pair of objects, from apples and books to stars and moons. For example, the force

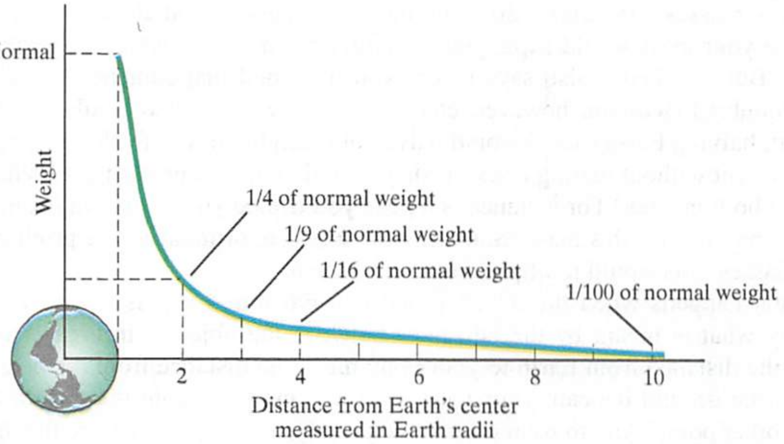


Figure 5.6
A graph of your weight at various distances from Earth's center. The same graph applies to the weight of any object.

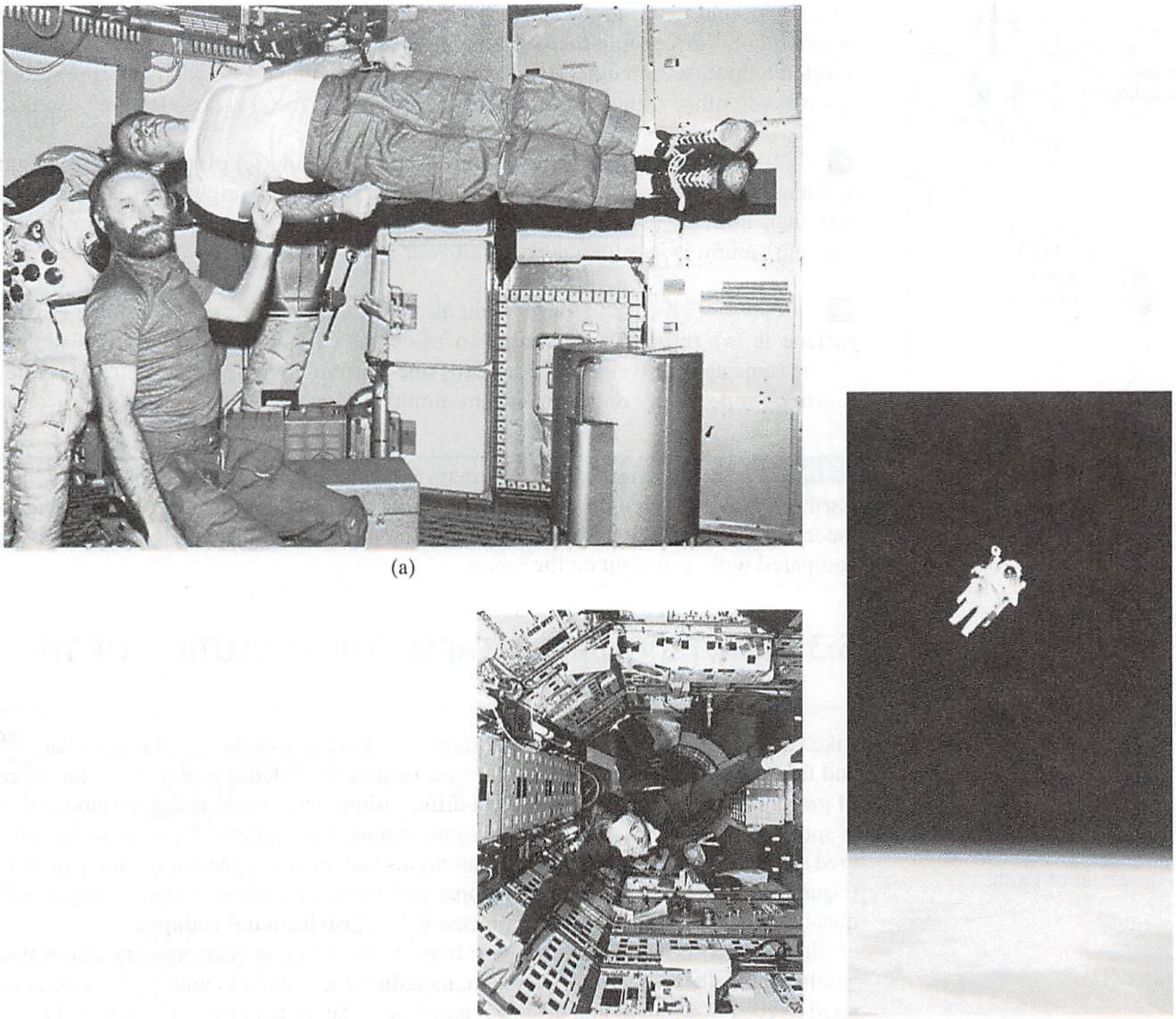
between a kilogram and another kilogram 1 meter away is found by putting these numerical values into the gravitational force formula. The answer is 6.7×10^{-11} newtons, or 0.000 000 000 067 newtons! It's no wonder that the gravitational force between ordinary objects is difficult to detect. The delicate experiments needed to measure such tiny forces could not be performed until about a century after Newton's work. When they were performed, they verified Newton's predictions.

The situation inside an orbiting satellite seems paradoxical. Judging from Figure 5.7, you would feel weightless in an orbiting satellite, at any altitude. But you have seen that if the satellite is in low orbit, your weight is actually only a little less than normal. Why, then, would you *feel* weightless, even though you are not *really* weightless? To answer this, let's imagine a somewhat similar situation (Figure 5.8): Suppose you are in an elevator and the elevator cable breaks. The elevator is then in free fall, and so are you. After the cable breaks, your feet no longer press down against the floor. If you try to press your feet against the floor, you will simply push yourself away from the floor. A bathroom scale glued to your feet would read zero, because your feet would not press down on it. You are apparently weightless, but, because we have defined weight as the gravitational force on an object, you are not really weightless. Although you have not (I hope) actually experienced a freely falling elevator, you might have experienced a similar "weightless" effect in a roller-coaster while moving rapidly over a crest in the track.

You would feel weightless in an orbiting satellite for the same reason that you would feel weightless in a freely falling elevator. As you saw in the preceding section, the satellite falls freely around Earth. You are falling freely around Earth too, regardless of whether you are inside the satellite or outside in space. Since both you and the satellite are just falling around Earth, you have the sensation of **weightlessness.** Your body behaves as though it were removed from the effects of gravity, but you are not really weightless.

How do we know Newton's theory of gravity? How did Newton verify his theory of gravity? The dependence on mass was not hard to deduce. Because an object's weight is proportional to its mass (for instance, two identical apples glued together surely have twice the weight of one, so doubling the mass doubles the weight), Newton reasoned that the force of gravity must be proportional to each of the two masses.

But what about the dependence on distance? Newton knew that the distance to the moon is about 60 times larger than Earth's radius (Figure 5.9). Newton's theory of gravity then implies that an object at the moon's distance should experience a force that is 3600 (the square of 60) times smaller than the force on the same object on Earth. So


(a)

(b)

(c)

Figure 5.7
Space travelers feel weightless when they are in orbit and at any other time that they are "falling" freely through space. (a) Balancing. (b) Floating. (c) Spacewalking.

(since acceleration is proportional to force) the acceleration of an object at this distance should be 3600 times smaller than the acceleration of an object falling to Earth. In other words, Newton's hypothesis implies that the moon's acceleration should be (1/3600) × 9.8 m/s^2, or 0.0027 m/s^2. But from the known distance to the moon, plus the observed fact that the moon takes 27 days to complete a circle around Earth, Newton could calculate directly that the moon's acceleration (due to its circular motion) actually is 0.0027 m/s^2. Newton's theory agreed with the observation.

CONCEPT CHECK 5 Suppose that you were in distant space, far from all planets and stars, and you placed an apple and a book at rest in front of you, separated by about 1 m, and then moved some distance away in order to observe the apple and book without influencing them. The apple and the book would then (a) very slowly accelerate toward each other; (b) very rapidly accelerate toward each other; (c) move toward each other without accelerating; (d) remain at rest; (e) head for the beach.

Figure 5.8
Falling freely in a freely falling elevator.

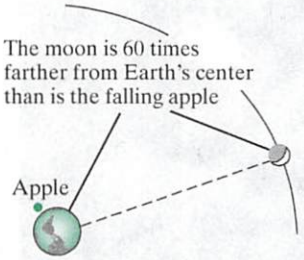


Figure 5.9
The moon is 60 Earth radii away from the center of Earth.

▶ CONCEPT CHECK 6 When you are in a high-flying jet plane, (a) your weight and mass are both normal (the same as on Earth); (b) your weight and mass are both less than normal; (c) your weight is normal but your mass is less than normal; (d) your weight is less than normal but your mass is normal.

▶ CONCEPT CHECK 7 Your weight at an altitude of 2 Earth radii above Earth's surface is (a) zero; (b) impossible to calculate without knowing Earth's radius; (c) the same as your weight on Earth; (d) one-third of your weight on Earth; (e) one-fourth of your weight on Earth; (f) one-ninth of your weight on Earth.

MAKING ESTIMATES Earth's mass is about 100 times the moon's mass, and Earth's radius is about 4 times the moon's radius. From this information, use Newton's theory of gravity to quickly estimate how much more an object weighs on Earth, as compared with its weight on the moon.

5.3 GRAVITATIONAL COLLAPSE: THE EVOLUTION OF THE SOLAR SYSTEM

Like you and me and everything else, stars have a beginning, they go through changes, and they have an ending. The driving force behind this "stellar evolution" is the force of gravity. Stars are made mostly from diffuse (thin) gas, mostly hydrogen atoms, that is spread throughout the universe. In some regions, this material happens to be gathered slightly more densely into great gas clouds that are the spawning grounds for stars (**Figure 5.10**). Because of the gravitational pull between all bits of matter, all gas and dust in space tends to aggregate, a process called **gravitational collapse.**

Here is how the sun and Earth were born. Some 5 billion years ago, the atoms that would eventually form the solar system, including every atom in your body, were scattered as cold, diffuse gas and dust over a region far larger than the solar system. Then a blast of radiation and fast-moving particles from a nearby exploding star (more about this later) caused turbulence and clumping in this gas and dust. Such a clump of matter, if sufficiently dense, will gravitationally attract more gas and dust, causing still stronger gravitational forces, pulling even more matter inward, and so forth in a self-reinforcing buildup of matter. As our clump of gas and dust became more massive and more dense, atoms fell at greater and greater speeds toward the center, where they collided and formed a central region of fast-moving atoms. In other words, the center heated up.

Every gas cloud spins a little, simply from the net effect of its chaotic flowing and swirling. As our gas cloud contracted, this spinning increased, just as a figure skater spins faster and faster as she brings her outstretched arms into her sides.[2] As

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[2] This is because of something called "conservation of angular momentum," a sort of rotational version of conservation of momentum (Chapter 4).

SOLUTION TO MAKING ESTIMATES In the theory of gravity, one of the masses is multiplied by 100 and R is multiplied by 4. Thus F is multiplied by $100/4^2 = 100/16$, or about 6. So your weight is six times larger on Earth than on the moon.

Figure 5.10
Star birth. These eerie, dark, pillar-like structures are columns of cool interstellar hydrogen gas and dust that are also incubators for new stars. They are part of the Eagle Nebula, a nearby star-forming region in our own galaxy. This region is "only" 7000 light-years away (i.e., it takes light 7000 years to get here from there). The tallest pillar (left) is about 1 light-year long from base to tip—a distance that is about 800 times larger than the distance across our solar system. This is one of the many beautiful and informative photographs taken by the Hubble Space Telescope, shown in Figure 1.2(a).

contraction continued, this spinning became rapid enough to flatten the outer regions of the gas ball into a disk, much as a wad of dough can be flattened to make a pizza by spinning it. Some of the gas in the outlying disk rotated fast enough to go into orbit around the larger central ball. Because it was orbiting, this material was left behind as the center collapsed. The outer region continued orbiting while cooling, condensing, and aggregating into clumps that became Earth and the other planets (**Figure 5.11**).

As the warming sun got hot enough to glow, light streaming outward swept away the dust and gas that had filled the solar system. And then there was light on Earth.

The central ball continued collapsing and heating until the center reached million-degree temperatures. New things happen at such temperatures: Atoms collide so violently that their electrons are stripped off, leaving a gas made mostly of bare hydrogen nuclei and electrons. The violently colliding hydrogen nuclei occasionally stick together, a process known as **nuclear fusion** (Chapter 16). Nuclear fusion creates lots of heat, and the pressure from this heat then prevents the ball of gas from collapsing further. When it initiated nuclear fusion nearly 5 billion years ago, our sun turned itself on and became a normal, self-sustaining star. A similar process of star birth is going on all the time, all over the universe. The starry sky is not static.

Scientists have recently learned that our sun had a violent birth amidst high-energy radiation and explosions of entire stars. Based partly on material found in meteorites that formed along with the solar system, it's now known that one or more nearby stars must have exploded during the solar system's formation. It's thought

Figure 5.11
An imaginary view of the newborn sun during formation of the solar system. Dust partially obscures the sun. As comets streak by, a planet (foreground) begins to form from the dust.

that the sun and some 50 or more other stars all formed at roughly the same time from a single huge region of gas and dust within our Milky Way Galaxy (our galaxy was already some eight billion years old by then). The upper, lit-up, portion of the left-hand "pillar" in Figure 5.10 is an example of such a star-forming region within our galaxy today. At least a few very massive stars, far more massive than the sun, are likely to form in such regions. Any such massive star "burns" (via nuclear fusion) very hot and therefore very rapidly, and soon exhausts itself in a giant **supernova explosion** (more on this in the next section). High energy radiation and ejected particles from such massive stars, as well as the blast effects from supernova explosions themselves, then initiated the formation of smaller stars as described in the preceding paragraph, and also helped shape such star formation processes.

Once our sun stopped collapsing, it settled into a middle age that has been going on for nearly 5 billion years. The long-term stability of this period made it possible for atoms on one planet to gather and evolve into highly complex forms such as ourselves. Like the rest of the solar system, we came from the universe.

But stars eventually die. Over billions of years, our sun's supply of hydrogen fuel must deplete until, around the year 5,000,000,000 CE, it will no longer support nuclear fusion in its central "core." Then the sun will enter old age. Although nuclear fusion will cease near the sun's center, a thin outer shell of hydrogen will continue the fusion process, causing the sun to brighten and expand to three times its present size. The increased energy output will evaporate Earth's oceans and perhaps cause a runaway greenhouse effect (Chapter 9) that could make Earth even hotter than Venus's 500°C. During the following several hundred million years, the sun will become still brighter and 100 times larger, warming Earth to around 1000°C and killing any remaining life.

By this time, the central core will have grown hot enough to ignite new, hotter nuclear reactions involving the element helium. The sun will then spend 100 million years as a helium-burning star. Then comes another disaster. After exhausting its helium, the sun will again expand, brighten, and eject its outer layers in a huge shell of glowing gas that will expand outward, engulfing all the planets and drifting outward beyond the solar system into interstellar space. After a million years of this, the sun will have entirely exhausted its energy sources.

Gravity will assert itself for the final time. Without a nuclear heating source, there will be little to stop the sun from collapsing inward on itself. Certainly the interatomic forces that hold up solid matter against outside pressures on Earth are far too puny to stand up against the enormous inward pull of gravity in the final collapse of a star. The sun will squeeze itself far inside its present boundaries and far inside the volume it would have if it were made of ordinary solid material, squashing its atoms out of recognizable existence until only a solid, tightly packed ball of bare nuclei and unattached electrons remains. At this point, the collapse will be permanently stopped by an effect known as "quantum exchange forces" between the electrons.[3]

The sun's burnt-out corpse will be hot, solid, and about Earth's size, or one-millionth of its present volume! It will be extraordinarily compact, with many tonnes packed into each cubic centimeter. On Earth, even a solid steel platform would be unable to support a mere thimbleful of this material. The sun will warm enormously during its final collapse, but once the collapse ends there will be no further source of heating. This starry remnant will glow brightly for a while and then slowly dim like a dying ember, still orbited by the charred remains of Earth and other planets.

A star the size of Earth? When such an object was first discovered in 1862, astronomers thought there must be an error in their observations. But two other such stars were soon discovered, and it's now known that about 4% of the stars in our galaxy—some 16 billion stars—are of this type. Because of their white-hot glow they are called **white dwarfs.**

How do we know our solar system's past and future? Detailed quantitative theories predict the scenario just sketched. Observations of stars in the various evolutionary stages described and observations of Earth's oldest rocks, the moon, moon rocks, meteorites, other planets, other moons, and the sun itself all support these theories.

The natural place to look for star births is among thick gas clouds in space. When the Hubble Space Telescope searched the dense gas cloud known as the Eagle Nebula, it found thousands of newly minted stars (Figure 5.10). Just as the theory predicts, nearly all of these new stars were wrapped in disks of dust and gas, disks that are expected eventually to coalesce into planets.

CONCEPT CHECK 8 Suppose that the sun collapsed tomorrow to become a white dwarf, but without any explosions or expansion that would alter the sun's mass or directly impact Earth. Which of the following would ensue? (a) Earth's orbit would be altered. (b) Life on Earth would be radically affected. (c) The gravitational force by the sun on Earth would be radically altered. (d) The sun's radiation would be radically altered. (e) None of the above.

5.4 GRAVITATIONAL COLLAPSE: THE DEATHS OF MORE MASSIVE STARS

My suspicion is that the universe is not only queerer than we suppose, but queerer than we can suppose.

John B. S. Haldane, British Geneticist, 1892–1964

A star's life cycle is determined primarily by its mass. A star needs at least 10% of the sun's mass in order to get hot enough to initiate nuclear fusion and become a star in the first place. All stars massive enough to initiate nuclear fusion go through a middle age that is similar to the sun's present state. Then when the hydrogen fuel

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[3] Quantum exchange forces have no explanation within Newtonian physics. They are far stronger than the ordinary electrical forces that maintain the solidity of normal solid matter.

in their central cores have been used up, they enter their final phases. Stars having masses up to about 10 times the sun's mass go through a final phase similar to the sun's, ending as white dwarfs.

But a quite different fate awaits more massive stars. Like the sun, they use up their hydrogen fuel and then contract at the center. But the larger mass makes the contraction stronger, so the center gets hotter. The high temperature initiates a wide range of nuclear reactions that eventually turn the star's small central core into solid iron. This gets the star into serious trouble. Iron continues forming until the inner core becomes so massive that it cannot hold itself up. The entire solid iron core then abruptly collapses in just one second! As the core collapses, this unimaginably cataclysmic **supernova explosion** blasts the rest of the star into space. For a brief moment, the dying star glows as brightly as 4 billion suns.

No supernova has been seen in our galaxy since 1604, but today astronomers are able to routinely discover them in other galaxies. The nearest of these burst into view in 1987 and was visible to the naked eye (**Figure 5.12**). It occurred in a neighboring small galaxy at a safe distance of 150,000 light-years (meaning that light travels from there to here in 150,000 years). A nearby supernova, if it were as close as 10 light-years or so, would produce various radiations that would create a fabulous light show in Earth's atmosphere, and that would soon kill us. But not to worry: Such an event won't happen in our corner of the Galaxy, because a candidate star for a supernova must be at least 10 times as massive as the sun and there's nothing that massive that close. The nearest likely candidate is Betelgeuse, which has been acting unstable for years. But it's at a safe 430 light-years away.

Only 10% to 20% of the original star remains after the explosion. No further nuclear reactions can occur in this remnant, so there is little to oppose the inward pull of gravity. Within one second, this remaining massive core collapses to become one of the two densest things in the universe, a neutron star or a black hole.

If the original star had a mass of between 10 and 30 suns, the final collapse is strong enough that electron exchange forces (see the previous section) can't stop it.

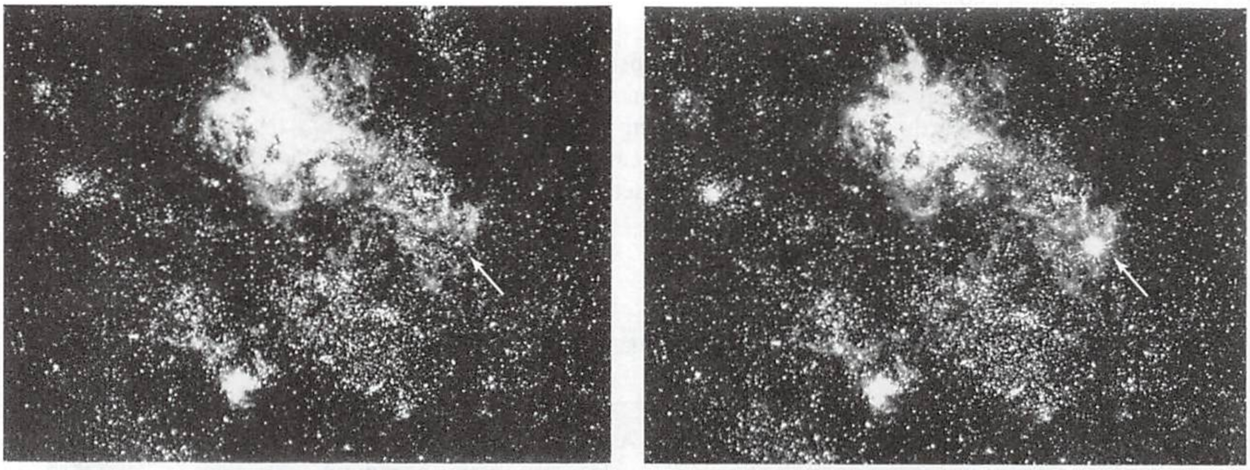
(a) (b)

Figure 5.12
The supernova of 1987, the brightest supernova in 400 years. Its light reached Earth on February 23, 1987. "Before" (a) and "after" (b) photos show the star as it looked before and shortly after the explosion. The supernova is the bright star on the right in figure (b).

But there's one remaining force that does stop it, the so-called "neutron exchange force," a quantum effect similar to the electron exchange force but acting between neutrons. The collapse not only squashes atoms out of existence, it also squashes electrons out of existence by forcing them to merge with protons in the nuclei. This turns each nucleus into a collection of neutrons, and it turns the entire star into an object that resembles a giant nucleus made of neutrons. It's called a **neutron star.**

Nuclear physicist J. Robert Oppenheimer, who later gained fame as leader of the team that developed the atomic bomb (Chapter 15), predicted neutron stars in 1938. None were discovered until 1967, when Jocelyn Bell (Figure 5.13), a sharp-eyed astronomy graduate student in England, discovered a source of radio waves in space that sent out "beeps" or "pulses" every 1.3 seconds. Some scientists thought at first that she might have discovered a radio beacon from an extraterrestrial civilization. But another was soon discovered, and by now hundreds are known, with a wide range of pulse rates. There's little doubt that they are neutron stars.

Figure 5.13

Jocelyn Bell (later Burnell) discovered the first four neutron stars. Using a radio telescope that she helped build as part of her Ph.D. dissertation, Bell detected a rapid set of pulses occurring at regular intervals. She determined that the position of the unusual radio source remained fixed with respect to the stars, which meant that it was located beyond the solar system. During the course of the next few months, she discovered three more pulsating radio sources. These were later found to be rapidly rotating neutron stars.

A neutron star is pretty impressive. More massive than the sun, the star is only a few kilometers across with a billion tonnes packed into each cubic centimeter! On Earth, a barely visible speck of this material would weigh as much as a large, fully loaded highway truck! The collapsing iron core spins faster and faster during its one-second collapse, so that the remnant neutron star spins at incredible speeds for such a massive object—up to 700 times every second. The surface of such a rapidly spinning neutron star moves at an incredible 15% of the speed of light. This is staggering when you realize that the star has a mass of some 10^{27} tonnes. This spinning combines with magnetic effects to create the rapid pulses of visible light and radio signals observed from Earth, the signals that Bell discovered in 1967. As seen from Earth, the entire star appears to flash on and off many times every second. Figure 5.14 is a sequence of photographs showing two of these visible flashes. The supernova explosion that created this neutron star was seen and recorded on Earth in 1054. For a few days the light from the explosion was brighter than the planet Venus. Today, it's called the Crab Nebula because the shape of the nebulous halo of gases blown into space by the explosion resembles a crab.

Neutron stars pull hard. The star's radius is only about 10 kilometers, which is 100,000 times smaller than the sun's radius. Yet the star is more massive than the sun. Newton's theory of gravity tells us that the weight of an object on the surface of a star is proportional to the inverse of the square of the star's radius. If a collapsing star's radius becomes 10^5 times smaller, an object on its surface becomes $10^5 \times 10^5 = 10^{10}$ (10 billion) times heavier. That's heavy.

What about stars even more massive than those that collapse to form neutron stars—stars having a mass of over 30 suns? When such a star runs out of fuel, the ensuing collapse is so strong that no known force can stop it. According to current theories, it collapses into a single point! Its matter—its atoms and subatomic particles—is squeezed out of existence. The star retains its mass, however, and so it retains its gravitational influence on the space around it. This star pulls really hard. If you had the misfortune to get too close, you could not escape, because gravity won't let anything escape—not even light itself. That's why it's called a **black hole.** For a typical black hole formed from a collapsing giant star, the distance within which nothing can escape is 10 to 50 km (larger for more massive black holes). You can think of this as the "radius" of the black hole. If you were within this distance of the central point and you wanted to throw an object completely away from the

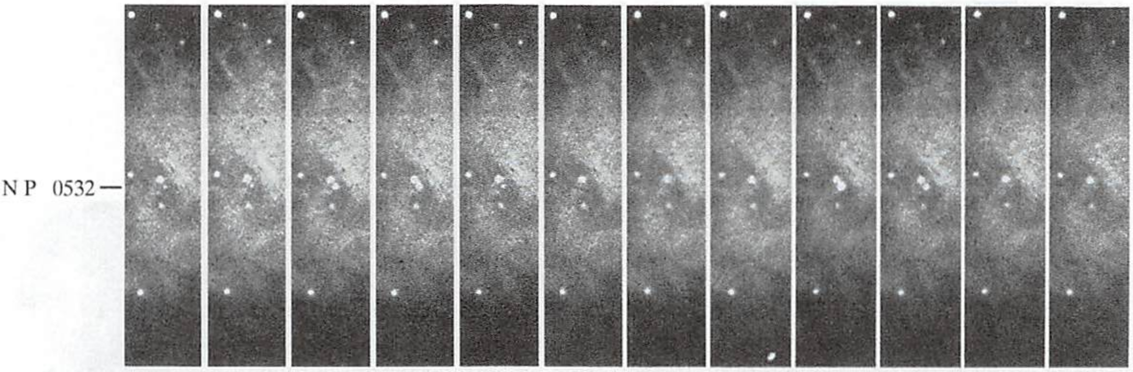

Figure 5.14
A sequence of photographs of the neutron star at the center of the Crab Nebula. Portions of a surrounding gas cloud, the remnant of the supernova explosion that created the neutron star, can be seen. This sequence lasts 1/20 second and includes two flashes, the first during frames 3 and 4, and the second during frames 9 and 10.

star, you would need to throw it faster than the speed of light. But objects cannot be thrown faster than light (see Chapter 10). So nothing can escape a black hole.[4]

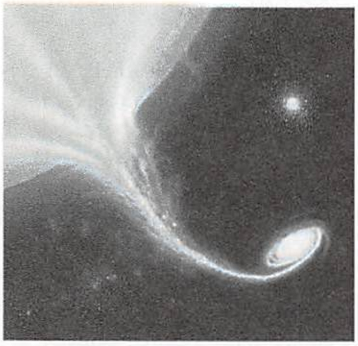

Figure 5.15
In this artist's conception, a black hole pulls matter from a companion star and accelerates it into a hot, X-ray–emitting disk before slowly swallowing it.

How do we know that black holes exist? Scientists detect black holes by their gravitational influence on things around them. The first black hole, Cygnus X-1, was discovered in 1972. It's thought to be a double star, two stars orbiting each other. One is a visible giant star, the other an unseen compact (far smaller than a normal star) object. By observing its gravitational effect on the visible star, the compact object's mass can be deduced to be 10 solar masses.[5] Since theories indicate that a compact object of more than 3 solar masses can only be a black hole, astronomers believe that Cygnus X-1 is a black hole. Satellites in orbit around Earth detect X-rays from Cygnus X-1 that further confirm it to be a black hole. Apparently the invisible object's gravitational pull is drawing gases from the visible star and accelerating them down into and around the black hole, a process that tears apart the gas atoms and causes them to emit X-rays that scientists can observe (**Figure 5.15**). Astronomers have now identified about 20 similar objects within our galaxy that are thought to be black-hole remnants of collapsed stars, and they suspect that there might be around one billion of them in our galaxy.

Scientists don't go out of their way to invent bizarre ideas like black holes. To the contrary, they look for the least strange explanation of the data. For example, people once found it strange that Earth could orbit the sun, but astronomers such as Copernicus found that this was the most natural way to account for the data. In the same manner, astronomers today find that a black hole is the most natural explanation for what they observe at Cygnus X-1. If it is not a black hole, then this object is not compact, or it does not have a mass larger than 3 suns, or compact objects of greater than 3 solar masses are not always black holes. Astronomers find it easier or "less strange" to believe that Cygnus X-1 is a black hole than to believe any of these options.

There is a second kind of black hole for which the evidence is even more compelling than it is for Cygnus X-1. The centers of most galaxies contain extremely massive black holes. In 1994, for example, the Hubble Space Telescope found a tiny, bright source of

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[4] More precisely, quantum theory allows black holes to emit subatomic particles, but this effect is negligible for collapsed stars. This effect is expected to be important for low-mass black holes, although such small black holes have never been observed and may not exist.

[5] The original star, before collapse, had a mass of more than 30 suns, but most of this mass blew into space during the collapse.

light at the center of a distant galaxy. Detailed analysis of this light showed that nearby gas and stars are orbiting this center so rapidly that gravity can hold them in their orbits only if the bright object has a mass of several *billion* suns. Given that the central object's size is only slightly larger than our solar system, it could only be a black hole. The light apparently comes from high-energy processes occurring just outside the black hole.

Study of distant galaxies reveals that the centers of most or all of them contain black holes having masses of millions or billions of suns. The distant and powerful objects known as "quasars" are powered by such giant black holes. Observation of a small portion of sky, and extrapolation to the entire sky, leads to an estimate of at least 300 billion giant black holes populating the observable universe! Observations of stars dashing in tight orbits around the center of our own Milky Way Galaxy at up to 1/30th of the speed of light imply a giant black hole lurks there. Despite having a mass of nearly 4 million suns, it is only about 20 times larger than our sun! Such giant black holes radiate X-rays and light as they swallow nearby stars and gas. Their origin is not yet understood.

CONCEPT CHECK 9 If Earth collapsed from its present 6000 km radius to only 6 km, your weight would be (a) unchanged; (b) 1/1000th of your present weight; (c) 1/1,000,000 of your present weight; (d) 1000 times your present weight; (e) 1,000,000 times your present weight.

5.5 THE NEWTONIAN WORLDVIEW: A DEMOCRATIC, MECHANICAL UNIVERSE

During the sixteenth and seventeenth centuries, the new sun-centered astronomy and inertial physics ushered in a new philosophical and religious view that I'll call the **Newtonian worldview.**[6] It is one of the most significant consequences of Newtonian physics. Even though Newtonian scientific ideas have been partly superseded by other more accurate theories, the worldview based on Newtonian physics retains its influence on popular culture.

> I am much occupied with the investigation of the physical causes [of the motions of the solar system]. My aim is to show that the heavenly machine is not a kind of divine, live being, but a kind of clockwork... insofar as nearly all the manifold motions are caused by a most simple, magnetic, and material force, just as all motions of a clock are caused by simple weight.
>
> Kepler

In the Western world, the pre-Newtonian worldview combined medieval Christianity, the Earth-centered astronomy of the ancient Greeks, and Aristotle's physics. Central to this view was the idea of purpose, or future goals. During the Middle Ages in Europe, popular culture united with religion and science in the belief that there was a purpose for everything and that the universe's larger purposes were tied to humans, so that humankind was central to all creation. Ancient Earth-centered astronomy and Aristotelian physics, with its goal-directed natural motions (Section 3.1), chimed in perfectly with this traditional view. It was well attuned to the era's hierarchical social structure, comprising a God-ordained king surrounded by a few land-holding nobles surrounded in turn by many land-working serfs and peasants.

Astronomy and physics since the Middle Ages have contradicted Earth-centered astronomy and Aristotelian physics. Copernicus removed Earth from the center, Kepler replaced the planets' "natural" circular orbits with ellipses, and Descartes declared that bodies move not because they have a goal but simply because there is nothing to stop them. The hierarchy of natural places, the notion that Earth is special, the centrality of humankind, and the scientific basis for purpose in the universe—all were swept away.

It was not by chance that stirrings for religious and political freedom began at about this time. Once the hierarchical cosmology began to crumble, it was no

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[6] Newton, Descartes, and Galileo were among the scientists and philosophers who contributed to this view.

longer obvious to people that they should follow the old hierarchical cultural habits. The new science established universal natural laws, rather than particular people or religious beliefs, as the ultimate framework for human behavior. Religious reformers such as Martin Luther felt freed to challenge medieval Christian traditions. Political reformer Thomas Jefferson could draw up a Declaration of Independence that threw off the divine rights of the king of England and that was permeated with the concept of "unalienable rights" flowing directly from "the Laws of Nature and of Nature's God" to all people as the basis for human equality. Thus does our science influence, on quite a deep level, our religion, our social order, and our politics.

Galileo sought only to describe how things behave, not why they behave as they do. He was not concerned with a physical phenomenon's purpose. Analysis—the new technique of separating phenomena into their simplest components and studying those components—was one of his tools. This led to a focus on the simplest and smallest components of matter: atoms. And so **atomism**—the idea that nature can be reduced to the motions of tiny material particles—underlay the new physics. For example, in a view remarkably similar to Democritus's view (Chapter 2), Newton stated:

> It seems probable to me that God in the beginning formed matter in solid, massy, hard, impenetrable, movable particles... and that these primitive particles being solids are incomparably harder than any porous bodies compounded of them, even so hard as never to wear or break in pieces....

[Men are] engines endowed with wills.

Robert Boyle

Newton, Galileo, and Descartes believed firmly in God. What place within the new science could be found for God? Descartes reconciled the new science with traditional religion by assuming that there were two realities, a notion known as **dualism.** The first reality was the material world, made of matter and operating according to nature's inflexible laws. Here, the true realities, or **primary qualities,** were assumed to be impersonal physical characteristics such as the motions of atoms. The second reality was spiritual, the realm of human thoughts and feelings and communication with God. These were assumed to be **secondary qualities** that were not part of the physical world but were merely reflections of the primary qualities. Thus did science and philosophy relegate human concerns to a shadowy secondary role in a physical universe.

This left little room for God in the workings of the material universe. In the traditional view, God is continually and actively present throughout the universe, continually endowing all things with purpose. In the new view, God is, at most, an uninvolved observer. Descartes and Galileo believed that God was needed to establish the laws of nature and to start the universe moving but that once started, the whole thing would run itself.[7]

Now I a fourfold vision see,
And a fourfold vision is given
  to me;
'Tis fourfold in my
  supreme delight
And threefold in soft
  Beulah's night
And twofold Always.
May God us keep
From Single vision
And Newton's sleep!

William Blake, 1757–1827, Poet, Painter, Rebel Against the Mechanical Single Vision, or Linear Thinking, of Newton

A machine, especially a finely tuned machine such as a clock, is an excellent analogy for the Newtonian worldview. Once the owner starts it, a clock runs itself according to its own operating principles. The founding fathers of physics thought of the universe as a clockwork mechanism whose operating principles were the laws of nature and whose parts were atoms. Because of its machinelike quality, I'll call this view the **mechanical universe.**

In fact, one major consequence of Newtonian physics is that every physical system is entirely predictable, like a perfectly operating clock. For a simple example, Newtonian physics can predict precisely how far a freely falling object will fall

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[7] With a few exceptions, Newton also believed that God did not intervene in the universe. On certain occasions, namely in situations for which Newton himself could not find a scientific explanation, he believed that God momentarily intervened. However, this "god of the gaps" view—that every phenomenon that cannot be explained by science requires an intervention by God—becomes less and less tenable as science closes the gaps.

during any specified time. This clocklike predictability has surprising implications. To understand them, imagine a simple, isolated, self-contained collection of atoms that move and interact in accordance with Newtonian physics. Suppose you specify the precise positions and velocities of every atom at one particular time. Then, according to Newton's theory of motion, the entire future behavior of this system can be precisely predicted, for all time.

But the Newtonian view is that the universe itself is just such a collection of atoms. Thus, the future is entirely determined by what all the atoms of the universe are doing right now or at any other time. Furthermore, since humans are entirely made of atoms, it follows that every thought or feeling that enters your head is reducible to the motion of atoms within your brain and elsewhere. Thus, all of your thoughts, feelings, and actions are entirely predetermined and predictable. You never choose to scratch your nose, for example—the laws of nature choose for you. You might believe that you choose, but this, too—this believing that you choose—was chosen for you by the laws of nature.

Such a mechanistic universe, the loss of free will, and the absence of a continuously creative God strike many observers as inhuman and cold. For example, German social scientist Max Weber (1864–1920) spoke of the "disenchantment of the world" brought about by Newtonian science. Poet and painter William Blake (1757–1827) wrote disdainfully in a poem "May God us keep/From Single vision/ and Newton's sleep!" Nevertheless, from the seventeenth into the twentieth century, these ideas influenced many educated people. Newtonian physics was so successful that the associated philosophy was accepted with little question. People absorbed the clockwork universe without knowing they were absorbing it.

There are reasons today to question both the Newtonian worldview and Newtonian physics (see the next section and Chapter 2). Nevertheless, it would be surprising if these views were not still influential today. A person's worldview tends to be absorbed thoughtlessly, as part of the cultural air of the times. It seems likely that the Newtonian worldview remains active, even (or perhaps especially) among people who have never heard of Isaac Newton.

It is for you, valued reader, to determine to what extent the Newtonian worldview is valid, whether it retains a significant influence, and what difference it might make.

5.6 BEYOND NEWTON: LIMITATIONS OF NEWTONIAN PHYSICS

Tested repeatedly during the eighteenth and nineteenth centuries, Newtonian physics stood up in quantitative detail to every challenge. In fact, it was so powerful and accurate that scientists began to accept it as true in an ultimate, absolute sense. But science is never absolute. Even though a scientific principle has been confirmed repeatedly, it hangs always by the slender thread of new experiments.

Around 1880, experimental results began appearing that couldn't be reconciled with Newtonian physics. The incorrect Newtonian predictions arose in four extreme situations: at high speeds, for enormous gravitational forces, at huge distances, and at tiny distances. During the first few decades of the twentieth century, Albert Einstein, Werner Heisenberg, and many others invented three new theories to account for these discrepancies: special relativity, general relativity, and quantum physics. To date, at least, scientists have found no exceptions to any of the new theories.

Experiments show that Newton's law of motion and Newtonian views of time and space break down at high speeds. The disagreement is not noticeable at slow

[It is unbelievable] that all nature, all the planets, should obey eternal laws, and that there should be a little animal, five feet high, who in contempt of these laws, could act as he pleased, solely according to his caprice.

Voltaire, French Philosopher and Writer, 1694–1778

They may say what they like; everything is organized matter.

Napoleon Bonaparte, 1769–1821

I never satisfy myself until I make a mechanical model of a thing. If I can make a mechanical model I can understand it. As long as I cannot make a mechanical model all the way through I cannot understand.

Lord Kelvin, Nineteenth-Century British Mathematician and Physicist

That Man is the product of causes which had no prevision of the end they were achieving; that his origin, his growth, his hopes and fears, his loves and his beliefs, are but the outcome of accidental collocations of atoms;... all these things, if not quite beyond dispute, are yet so nearly certain, that no philosophy which rejects them can hope to stand.

Bertrand Russell, Philosopher and Mathematician, 1872–1970

It's a material world.

Madonna

speeds, but the errors become worse as speeds increase. The non-Newtonian effects are difficult to detect for automobiles, jet planes, or even orbiting satellites moving at some 10 km/s. But at 30,000 km/s (around the world in about 1 second!), Newtonian predictions are off by 0.5%. At 290,000 km/s, nearly the speed of light, typical Newtonian predictions are incorrect by a factor of 4! Scientists didn't notice these non-Newtonian effects for 200 years because they had never closely studied such fast-moving objects. **Special relativity** gives correct predictions at all speeds, both low and high. These predictions become indistinguishable from Newtonian physics whenever the speeds are considerably less than the speed of light.

Similarly, experiments show that Newton's theory of gravity, Newton's law of motion, and Newtonian views about time and space are incorrect for objects subjected to enormous gravitational forces and also over huge distances. For example, non-Newtonian gravitational effects are measurable, but small, for the orbit of the innermost planet, Mercury, which feels strong gravitational forces from the sun. Non-Newtonian gravitational effects are pronounced near neutron stars and black holes and for physical systems that range over large portions of the observable universe. **General relativity** gives correct predictions for all these situations and is regarded as the correct theory of gravity. The predictions of general relativity become indistinguishable from Newtonian physics whenever gravitational forces are not too strong and distances are not too large.

The disagreements between Newtonian physics on the one hand and Einstein's special and general relativity on the other stem from profoundly different ways of viewing space and time. Newton took the common intuitive view that all of us take in our daily lives: Space is infinite in extent, time is infinite in duration, and both have the same properties everywhere and at all times. Einstein, however, found that space and time are "relative," or different for different observers, namely observers moving at different speeds. For example, the duration of a process such as the melting of your ice cream cone is different as viewed by you from its duration as viewed by your friend who is moving past you. From this, all sorts of new results emerge, such as that space can "curve," and time runs differently in different places. How can this be? For that, you'll need to consult Chapters 10 and 11.

Finally, experiments show that Newton's law of motion and subtle Newtonian views concerning predictability and cause and effect are incorrect for objects of molecular dimensions or smaller. **Quantum physics** gives correct predictions for objects of all sizes, from microscopic to macroscopic. For macroscopic objects like footballs and apples, quantum theory's predictions become indistinguishable from Newtonian physics.

Although quantum physics represents an even more profound revolution than does relativity, it stems from a seemingly insignificant difference concerning such properties as speed, momentum (Chapter 4), and energy (Chapter 6). Newtonian physics allows such properties to have any numerical value whatsoever within a continuous range of possibilities, for example, the speed of a particular airplane might be anything between zero and 1000 km/h. But quantum physics states that such properties can only have specific "permitted" values, such as 0.01 km/h, 0.02 km/h, 0.03 km/h, etc. up to 1000.0 km/h.[8] The speed of the airplane is said to be "quantized."

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[8] This is an exaggerated example for purposes of illustration; the differences between the permitted values would be much much smaller than this for a real airplane, and so this "quantization principle" isn't significant for airplanes and other large objects. But for microscopic objects, these "small" differences between permitted values are more important, and so quantization makes a big difference in the microworld.

As you'll see in Chapters 12 and 13, this turns out to have surprising and profound implications, especially in the microscopic world.

Figure 5.16 is one way of indicating, graphically, these limits of validity of Newtonian physics. The vertical axis represents the speed of individual objects. Special relativity predicts that objects cannot move faster than the speed of light—300,000 km/s—so these speeds are forbidden. The horizontal axis shows the size of individual objects. Because a principle known as "quantum uncertainty" predicts that objects cannot be both small[9] and slow moving, there is another forbidden region in the small-size, low-speed corner of the diagram.

The lesson is that it's not a Newtonian universe. Earth, where Newtonian physics works well for ordinary objects, is an exception in a universe dominated by relativistic and quantum phenomena. The conditions we regard as normal occur only rarely in the universe. Newtonian and intuitive concepts of time, space, matter, and much else are far from correct throughout most of the universe. As you will see in Chapters 10 through 17, the "real" universe—the quantum-relativistic universe—is fundamentally different, and far stranger, than our Earth-bound intuitions could have imagined.

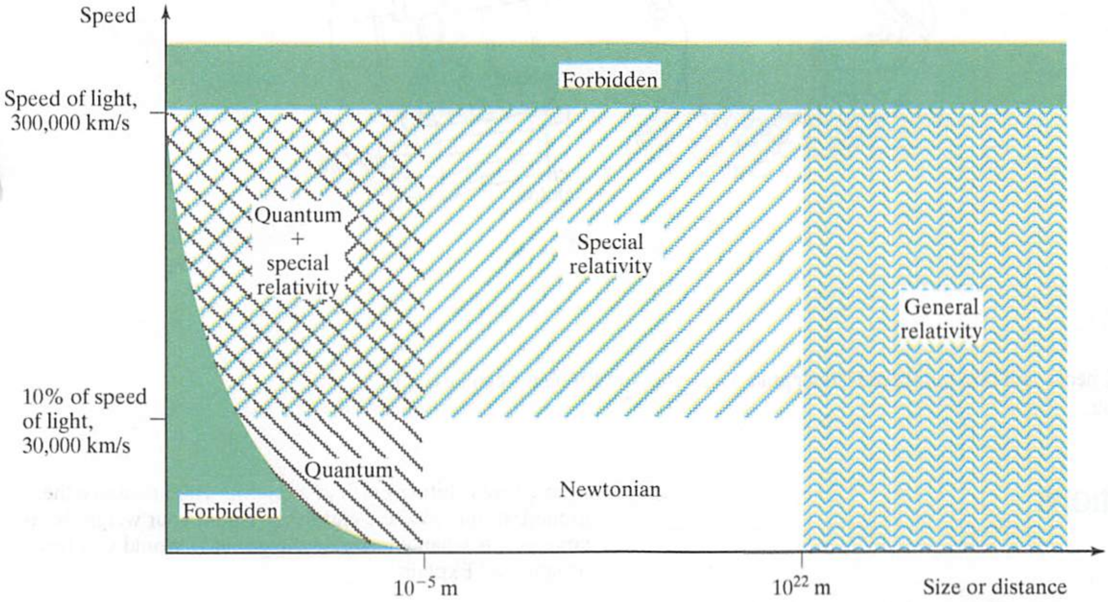

Figure 5.16[10]

Newtonian physics is correct for common phenomena on Earth, but breaks down for objects that are very small, very large, or very fast. Newtonian physics also breaks down for strong gravitational forces, such as those near a neutron star or black hole. The quantum and relativity theories apply throughout the entire range of the phenomena observed to date. The diagram is only schematic and approximate.

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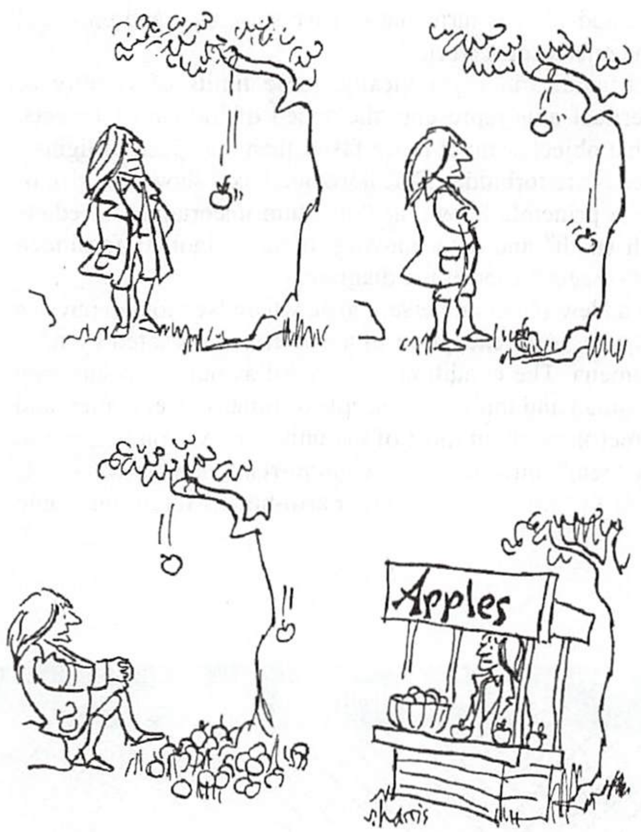
[9] "Highly localized" is a more accurate term than "small." A particle such as an electron is said to be "localized" within a small region of space when it is observed (or known) to be located within that region. The quantum uncertainty principle implies that a particle that is localized within a very small region must have (on the average) a high speed.

[10] Thanks to Douglas Giancoli, the author of several physics textbooks, including *Physics: Principles with Applications* (Englewood Cliffs, NJ: Prentice Hall, 1991), for suggesting diagrams of this type.



Answers to Concept Checks and odd-numbered Conceptual Exercises and Problems can be found in the back of the book.

Review Questions

THE IDEA OF GRAVITY

1. What is the direction of a falling apple's velocity? Of its acceleration?
2. What is the direction of the moon's velocity? Of its acceleration?
3. Does Earth exert a force on the moon? What is its direction? How would the moon move if this force suddenly vanished?
4. In what ways are the moon and a falling apple similar? In what ways do they differ?

NEWTON'S THEORY OF GRAVITY

5. Does this book exert a gravitational force on your body?
6. What would happen to this book's weight if you managed to double Earth's mass? What if, instead, you doubled the book's mass? What if you doubled both?
7. In order to use Newton's theory of gravity to calculate your weight, what data would you need?
8. If you were orbiting Earth in a satellite 200 km above the ground, would you be weightless? Would your weight be as large as it is when you are on the ground? Would you feel weightless? Explain.

GRAVITATIONAL COLLAPSE

9. What caused the sun to get hot? What keeps it hot today?
10. Describe the process that formed the planets.
11. Since gravity pulls inward on the material in the sun and since the sun is made only of gas, why doesn't the sun collapse?
12. Are there places in our galaxy where stars are being born?
13. Name the process and also the substance that fuels the sun.
14. What will happen to the sun after it runs out of fuel?
15. Name and describe the object into which the sun will evolve after it runs out of fuel.
16. What causes different stars to evolve differently?
17. All stars eventually evolve into one of three types of objects. Name them. What kinds of stars evolve into each of the three types of objects?