

24

## Black Holes and Curved Spacetime

**Figure 24.1 Stellar Mass Black Hole.** On the left, a visible-light image shows a region of the sky in the constellation of Cygnus; the red box marks the position of the X-ray source Cygnus X-1. It is an example of a black hole created when a massive star collapses at the end of its life. Cygnus X-1 is in a binary star system, and the artist's illustration on the right shows the black hole pulling material away from a massive blue companion star. This material forms a disk (shown in red and orange) that rotates around the black hole before falling into it or being redirected away from the black hole in the form of powerful jets. The material in the disk (before it falls into the black hole) is so hot that it glows with X-rays, explaining why this object is an X-ray source. (credit left: modification of work by DSS; credit right: modification of work by NASA/CXC/M.Weiss)

### Chapter Outline

- 24.1 Introducing General Relativity
- 24.2 Spacetime and Gravity
- 24.3 Tests of General Relativity
- 24.4 Time in General Relativity
- 24.5 Black Holes
- 24.6 Evidence for Black Holes
- 24.7 Gravitational Wave Astronomy



### Thinking Ahead

For most of the twentieth century, black holes seemed the stuff of science fiction, portrayed either as monster vacuum cleaners consuming all the matter around them or as tunnels from one universe to another. But the truth about black holes is almost stranger than fiction. As we continue our voyage into the universe, we will discover that black holes are the key to explaining many mysterious and remarkable objects—including collapsed stars and the active centers of giant galaxies.

## 24.1 Introducing General Relativity

### Learning Objectives

By the end of this section, you will be able to:

- › Discuss some of the key ideas of the theory of general relativity
- › Recognize that one's experiences of gravity and acceleration are interchangeable and indistinguishable
- › Distinguish between Newtonian ideas of gravity and Einsteinian ideas of gravity
- › Recognize why the theory of general relativity is necessary for understanding the nature of black holes

Most stars end their lives as white dwarfs or neutron stars. When a *very* massive star collapses at the end of its life, however, not even the mutual repulsion between densely packed neutrons can support the core against its own weight. If the remaining mass of the star's core is more than about three times that of the Sun ( $M_{\text{Sun}}$ ), our theories predict that *no known force can stop it from collapsing forever!* Gravity simply overwhelms all other forces and crushes the core until it occupies an infinitely small volume. A star in which this occurs may become one of the strangest objects ever predicted by theory—a black hole.

To understand what a black hole is like and how it influences its surroundings, we need a theory that can describe the action of gravity under such extreme circumstances. To date, our best theory of gravity is the **general theory of relativity**, which was put forward in 1916 by Albert Einstein.

General relativity was one of the major intellectual achievements of the twentieth century; if it were music, we would compare it to the great symphonies of Beethoven or Mahler. Until recently, however, scientists had little need for a better theory of gravity; Isaac Newton's ideas that led to his law of universal gravitation (see [Orbits and Gravity](#)) are perfectly sufficient for most of the objects we deal with in everyday life. In the past half century, however, general relativity has become more than just a beautiful idea; it is now essential in understanding pulsars, quasars (which will be discussed in [Active Galaxies, Quasars, and Supermassive Black Holes](#)), and many other astronomical objects and events, including the black holes we will discuss here.

We should perhaps mention that this is the point in an astronomy course when many students start to feel a little nervous (and perhaps wish they had taken botany or some other earthbound course to satisfy the science requirement). This is because in popular culture, Einstein has become a symbol for mathematical brilliance that is simply beyond the reach of most people ([Figure 24.2](#)).



**Figure 24.2 Albert Einstein (1879–1955).** This famous scientist, seen here younger than in the usual photos, has become a symbol for high intellect in popular culture. (credit: NASA)

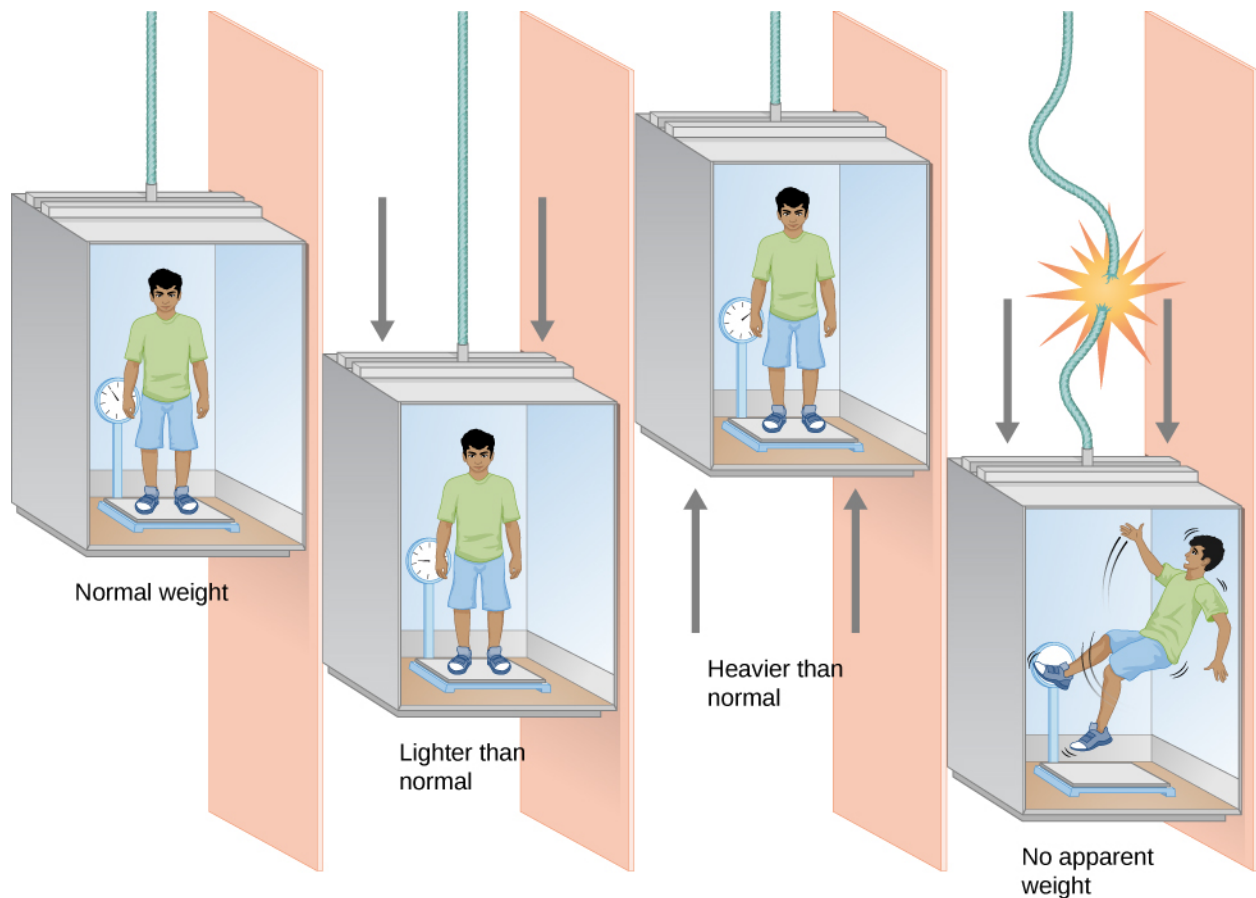
So, when we wrote that the theory of general relativity was Einstein's work, you may have worried just a bit, convinced that anything Einstein did must be beyond your understanding. This popular view is unfortunate and mistaken. Although the detailed calculations of general relativity do involve a good deal of higher mathematics, the basic ideas are not difficult to understand (and are, in fact, almost poetic in the way they give

us a new perspective on the world). Moreover, general relativity goes beyond Newton's famous "inverse-square" law of gravity; it helps *explain* how matter interacts with other matter in space and time. This explanatory power is one of the requirements that any successful scientific theory must meet.

### The Principle of Equivalence

The fundamental insight that led to the formulation of the general theory of relativity starts with a very simple thought: if you were able to jump off a high building and fall freely, you would not feel your own weight. In this chapter, we will describe how Einstein built on this idea to reach sweeping conclusions about the very fabric of space and time itself. He called it the "happiest thought of my life."

Einstein himself pointed out an everyday example that illustrates this effect (see [Figure 24.3](#)). Notice how your weight seems to be reduced in a high-speed elevator when it accelerates from a stop to a rapid descent. Similarly, your weight seems to increase in an elevator that starts to move quickly upward. This effect is not just a feeling you have: if you stood on a scale in such an elevator, you could measure your weight changing (you can actually perform this experiment in some science museums).



**Figure 24.3 Your Weight in an Elevator.** In an elevator at rest, you feel your normal weight. In an elevator that accelerates as it descends, you would feel lighter than normal. In an elevator that accelerates as it ascends, you would feel heavier than normal. If an evil villain cut the elevator cable, you would feel weightless as you fell to your doom.

In a *freely falling* elevator, with no air friction, you would lose your weight altogether. We generally don't like to cut the cables holding elevators to try this experiment, but near-weightlessness can be achieved by taking an airplane to high altitude and then dropping rapidly for a while. This is how NASA trains its astronauts for the experience of free fall in space; the scenes of weightlessness in the 1995 movie *Apollo 13* were filmed in the same way. (Moviemakers have since devised other methods using underwater filming, wire stunts, and computer graphics to create the appearance of weightlessness seen in such movies as *Gravity* and *The Martian*.)

## LINK TO LEARNING



Watch how NASA uses a “weightless” environment (<https://openstax.org/l/30NASAweightra>) to help train astronauts.

Another way to state Einstein’s idea is this: suppose we have a spaceship that contains a windowless laboratory equipped with all the tools needed to perform scientific experiments. Now, imagine that an astronomer wakes up after a long night celebrating some scientific breakthrough and finds herself sealed into this laboratory. She has no idea how it happened but notices that she is weightless. This could be because she and the laboratory are far away from any source of gravity, and both are either at rest or moving at some steady speed through space (in which case she has plenty of time to wake up). But it could also be because she and the laboratory are falling freely toward a planet like Earth (in which case she might first want to check her distance from the surface before making coffee).

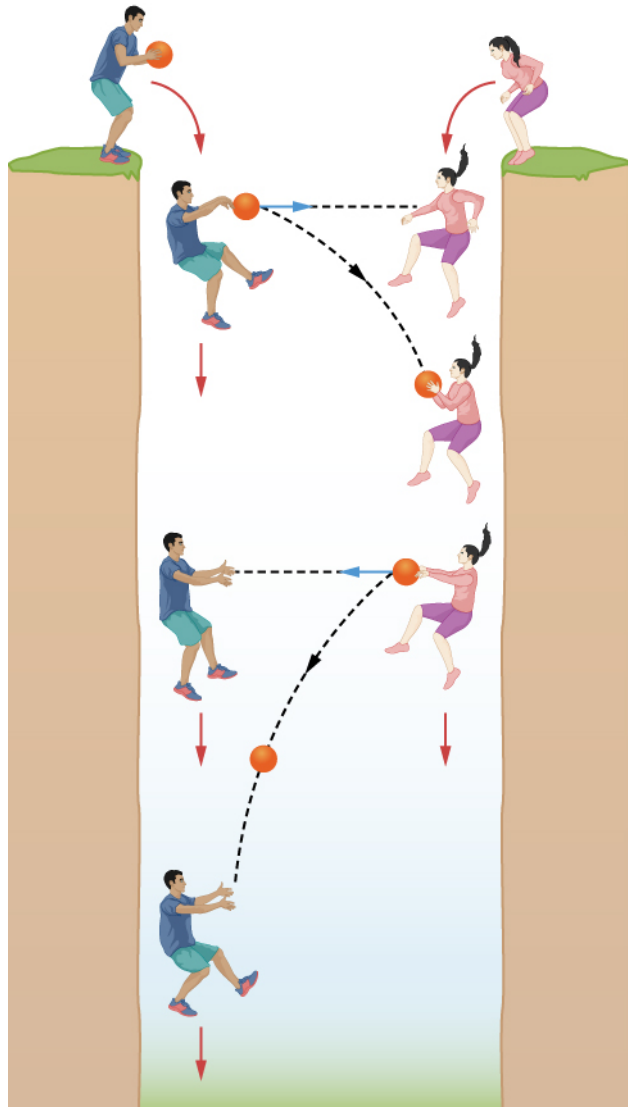
What Einstein postulated is that there is no experiment she can perform inside the sealed laboratory to determine whether she is floating in space or falling freely in a gravitational field.<sup>1</sup> As far as she is concerned, the two situations are completely *equivalent*. This idea that free fall is indistinguishable from, and hence equivalent to, zero gravity is called the **equivalence principle**.

### Gravity or Acceleration?

Einstein’s simple idea has big consequences. Let’s begin by considering what happens if two foolhardy people jump from opposite banks into a bottomless chasm ([Figure 24.4](#)). If we ignore air friction, then we can say that while they freely fall, they both accelerate downward at the same rate and feel no external force acting on them. They can throw a ball back and forth, always aiming it straight at each other, as if there were no gravity. The ball falls at the same rate that they do, so it always remains in a line between them.

---

<sup>1</sup> Strictly speaking, this is true only if the laboratory is infinitesimally small. Different locations in a real laboratory that is falling freely due to gravity cannot all be at identical distances from the object(s) responsible for producing the gravitational force. In this case, objects in different locations will experience slightly different accelerations. But this point does not invalidate the principle of equivalence that Einstein derived from this line of thinking.



**Figure 24.4 Free Fall.** Two people play catch as they descend into a bottomless abyss. Since the people and ball all fall at the same speed, it appears to them that they can play catch by throwing the ball in a straight line between them. Within their frame of reference, there appears to be no gravity.

Such a game of catch is very different on the surface of Earth. Everyone who grows up feeling gravity knows that a ball, once thrown, falls to the ground. Thus, in order to play catch with someone, you must aim the ball upward so that it follows an arc—rising and then falling as it moves forward—until it is caught at the other end.

Now suppose we isolate our falling people and ball inside a large box that is falling with them. No one inside the box is aware of any gravitational force. If they let go of the ball, it doesn't fall to the bottom of the box or anywhere else but merely stays there or moves in a straight line, depending on whether it is given any motion.

Astronauts in the International Space Station (ISS) that is orbiting Earth live in an environment just like that of the people sealed in a freely falling box (Figure 24.5). The orbiting ISS is actually “falling” freely around Earth. While in free fall, the astronauts live in a strange world where there seems to be no gravitational force. One can give a wrench a shove, and it moves at constant speed across the orbiting laboratory. A pencil set in midair remains there as if no force were acting on it.



**Figure 24.5 Astronauts aboard the Space Shuttle.** Shane Kimbrough and Sandra Magnus are shown aboard the Endeavour in 2008 with various fruit floating freely. Because the shuttle is in free fall as it orbits Earth, everything—including astronauts—stays put or moves uniformly relative to the walls of the spacecraft. This free-falling state produces a lack of apparent gravity inside the spacecraft. (credit: NASA)

### LINK TO LEARNING



In the “weightless” environment of the International Space Station, moving takes very little effort. Watch [astronaut Karen Nyberg \(https://openstax.org/l/30ISSzerogravid\)](https://openstax.org/l/30ISSzerogravid) demonstrate how she can propel herself with the force of a single human hair.

Appearances are misleading, however. There is a force in this situation. Both the ISS and the astronauts continually fall around Earth, pulled by its gravity. But since all fall together—shuttle, astronauts, wrench, and pencil—inside the ISS all gravitational forces appear to be absent.

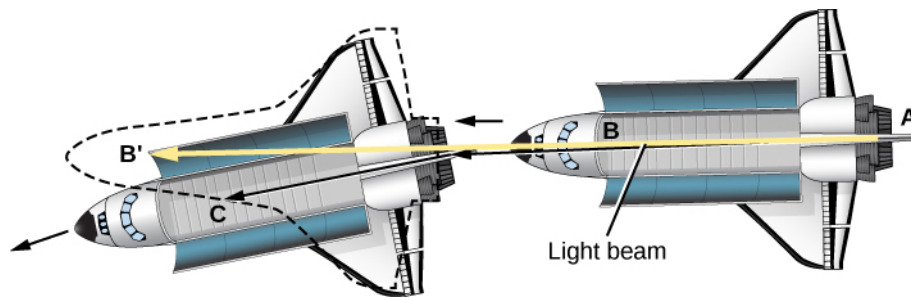
Thus, the orbiting ISS provides an excellent example of the principle of equivalence—how local effects of gravity can be completely compensated by the right acceleration. To the astronauts, falling around Earth creates the same effects as being far off in space, remote from all gravitational influences.

### The Paths of Light and Matter

Einstein postulated that the equivalence principle is a fundamental fact of nature, and that there is *no* experiment inside any spacecraft by which an astronaut can ever distinguish between being weightless in remote space and being in free fall near a planet like Earth. This would apply to experiments done with beams of light as well. But the minute we use light in our experiments, we are led to some very disturbing conclusions—and it is these conclusions that lead us to general relativity and a new view of gravity.

It seems apparent to us, from everyday observations, that beams of light travel in straight lines. Imagine that a spaceship is moving through empty space far from any gravity. Send a laser beam from the back of the ship to the front, and it will travel in a nice straight line and land on the front wall exactly opposite the point from which it left the rear wall. If the equivalence principle really applies universally, then this same experiment performed in free fall around Earth should give us the same result.

Now imagine that the astronauts again shine a beam of light along the length of their ship. But, as shown in [Figure 24.6](#), this time the orbiting space station falls a bit between the time the light leaves the back wall and the time it hits the front wall. (The amount of the fall is grossly exaggerated in [Figure 24.6](#) to illustrate the effect.) Therefore, if the beam of light follows a straight line but the ship’s path curves downward, then the light should strike the front wall at a point higher than the point from which it left.



**Figure 24.6 Curved Light Path.** In a spaceship moving to the left (in this figure) in its orbit about a planet, light is beamed from the rear, A, toward the front, B. Meanwhile, the ship is falling out of its straight path (exaggerated here). We might therefore expect the light to strike at B', above the target in the ship. Instead, the light follows a curved path and strikes at C. In order for the principle of equivalence to be correct, gravity must be able to curve the path of a light beam just as it curves the path of the spaceship.

However, this would violate the principle of equivalence—the two experiments would give different results. We are thus faced with giving up one of our two assumptions. Either the principle of equivalence is not correct, or light does not always travel in straight lines. Instead of dropping what probably seemed at the time like a ridiculous idea, Einstein worked out what happens if light sometimes does *not* follow a straight path.

Let's suppose the principle of equivalence is right. Then the light beam must arrive directly opposite the point from which it started in the ship. The light, like the ball thrown back and forth, *must fall with the ship* that is in orbit around Earth (see [Figure 24.6](#)). This would make its path curve downward, like the path of the ball, and thus the light would hit the front wall exactly opposite the spot from which it came.

Thinking this over, you might well conclude that it doesn't seem like such a big problem: why *can't* light fall the way balls do? But, as discussed in [Radiation and Spectra](#), light is profoundly different from balls. Balls have mass, while light does not.

Here is where Einstein's intuition and genius allowed him to make a profound leap. He gave physical meaning to the strange result of our thought experiment. Einstein suggested that the light curves down to meet the front of the shuttle because Earth's gravity actually bends the *fabric of space and time*. This radical idea—which we will explain next—keeps the behavior of light the same in both empty space and free fall, but it changes some of our most basic and cherished ideas about space and time. The reason we take Einstein's suggestion seriously is that, as we will see, experiments now clearly show his intuitive leap was correct.

## 24.2 Spacetime and Gravity

### Learning Objectives

By the end of this section, you will be able to:

- Describe Einstein's view of gravity as the warping of spacetime in the presence of massive objects
- Understand that Newton's concept of the gravitational force between two massive objects and Einstein's concept of warped spacetime are different explanations for the same observed accelerations of one massive object in the presence of another massive object

Is light actually bent from its straight-line path by the mass of Earth? How can light, which has no mass, be affected by gravity? Einstein preferred to think that it is *space and time* that are affected by the presence of a large mass; light beams, and everything else that travels through space and time, then find their paths affected. Light always follows the shortest path—but that path may not always be straight. This idea is true for human travel on the curved surface of planet Earth, as well. Say you want to fly from Chicago to Rome. Since an airplane can't go through the solid body of the Earth, the shortest distance is not a straight line but the arc of a *great circle*.

### Linkages: Mass, Space, and Time

To show what Einstein's insight really means, let's first consider how we locate an event in space and time. For

example, imagine you have to describe to worried school officials the fire that broke out in your room when your roommate tried cooking shish kebabs in the fireplace. You explain that your dorm is at 6400 College Avenue, a street that runs in the left-right direction on a map of your town; you are on the fifth floor, which tells where you are in the up-down direction; and you are the sixth room back from the elevator, which tells where you are in the forward-backward direction. Then you explain that the fire broke out at 6:23 p.m. (but was soon brought under control), which specifies the event in time. *Any* event in the universe, whether nearby or far away, can be pinpointed using the three dimensions of space and the one dimension of time.

Newton considered space and time to be completely independent, and that continued to be the accepted view until the beginning of the twentieth century. But Einstein showed that there is an intimate connection between space and time, and that only by considering the two together—in what we call **spacetime**—can we build up a correct picture of the physical world. We examine spacetime a bit more closely in the next subsection.

The gist of Einstein’s general theory is that the presence of matter curves or warps the fabric of spacetime. This curving of spacetime is identified with gravity. When something else—a beam of light, an electron, or the starship *Enterprise*—enters such a region of distorted spacetime, its path will be different from what it would have been in the absence of the matter. As American physicist John Wheeler summarized it: “Matter tells spacetime how to curve; spacetime tells matter how to move.”

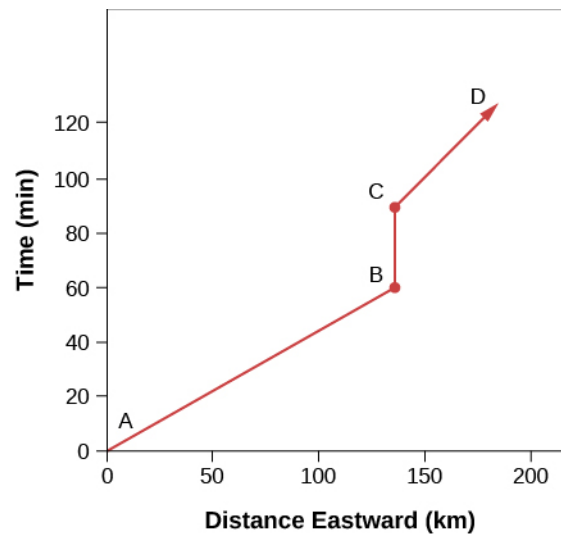
The amount of distortion in spacetime depends on the mass of material that is involved and on how concentrated and compact it is. Terrestrial objects, such as the book you are reading, have far too little mass to introduce any significant distortion. Newton’s view of gravity is just fine for building bridges, skyscrapers, or amusement park rides. General relativity does, however, have some practical applications. The GPS (Global Positioning System) in every smartphone can tell you where you are within 5 to 10 meters only because the effects of general and special relativity on the GPS satellites in orbit around the Earth are taken into account.

Unlike a book or your roommate, stars produce measurable distortions in spacetime. A white dwarf, with its stronger surface gravity, produces more distortion just above its surface than does a red giant with the same mass. So, you see, we *are* eventually going to talk about collapsing stars again, but not before discussing Einstein’s ideas (and the evidence for them) in more detail.

## Spacetime Examples

How can we understand the distortion of spacetime by the presence of some (significant) amount of mass? Let’s try the following analogy. You may have seen maps of New York City that squeeze the full three dimensions of this towering metropolis onto a flat sheet of paper and still have enough information so tourists will not get lost. Let’s do something similar with diagrams of spacetime.

[Figure 24.7](#), for example, shows the progress of a motorist driving east on a stretch of road in Kansas where the countryside is absolutely flat. Since our motorist is traveling only in the east-west direction and the terrain is flat, we can ignore the other two dimensions of space. The amount of time elapsed since he left home is shown on the *y*-axis, and the distance traveled eastward is shown on the *x*-axis. From A to B he drove at a uniform speed; unfortunately, it was too fast a uniform speed and a police car spotted him. From B to C he stopped to receive his ticket and made no progress through space, only through time. From C to D he drove more slowly because the police car was behind him.



**Figure 24.7 Spacetime Diagram.** This diagram shows the progress of a motorist traveling east across the flat Kansas landscape. Distance traveled is plotted along the horizontal axis. The time elapsed since the motorist left the starting point is plotted along the vertical axis.

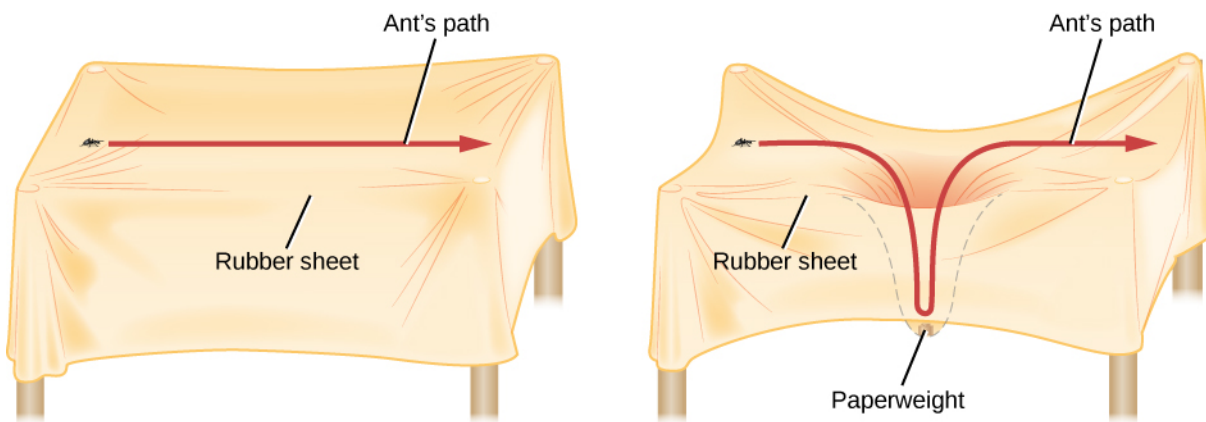
Now let's try illustrating the distortions of spacetime in two dimensions. In this case, we will (in our imaginations) use a rubber sheet that can stretch or warp if we put objects on it.

Let's imagine stretching our rubber sheet taut on four posts. To complete the analogy, we need something that normally travels in a straight line (as light does). Suppose we have an extremely intelligent ant—a friend of the comic book superhero Ant-Man, perhaps—that has been trained to walk in a straight line.

We begin with just the rubber sheet and the ant, simulating empty space with no mass in it. We put the ant on one side of the sheet and it walks in a beautiful straight line over to the other side (Figure 24.8). We next put a small grain of sand on the rubber sheet. The sand does distort the sheet a tiny bit, but this is not a distortion that we or the ant can measure. If we send the ant so it goes close to, but not on top of, the sand grain, it has little trouble continuing to walk in a straight line.

Now we grab something with a little more mass—say, a small pebble. It bends or distorts the sheet just a bit around its position. If we send the ant into this region, it finds its path slightly altered by the distortion of the sheet. The distortion is not large, but if we follow the ant's path carefully, we notice it deviating slightly from a straight line.

The effect gets more noticeable as we increase the mass of the object that we put on the sheet. Let's say we now use a massive paperweight. Such a heavy object distorts or warps the rubber sheet very effectively, putting a good sag in it. From our point of view, we can see that the sheet near the paperweight is no longer straight.



**Figure 24.8 Three-Dimensional Analogy for Spacetime.** On a flat rubber sheet, a trained ant has no trouble walking in a straight line. When a massive object creates a big depression in the sheet, the ant, which must walk where the sheet takes it, finds its path changed (warped) dramatically.

Now let's again send the ant on a journey that takes it close to, but not on top of, the paperweight. Far away from the paperweight, the ant has no trouble doing its walk, which looks straight to us. As it nears the paperweight, however, the ant is forced down into the sag. It must then climb up the other side before it can return to walking on an undistorted part of the sheet. All this while, the ant is following the shortest path it can, but through no fault of its own (after all, ants can't fly, so it has to stay on the sheet) this path is curved by the distortion of the sheet itself.

In the same way, according to Einstein's theory, light always follows the shortest path through spacetime. But the mass associated with large concentrations of matter distorts spacetime, and the shortest, most direct paths are no longer straight lines, but curves.

How large does a mass have to be before we can measure a change in the path followed by light? In 1916, when Einstein first proposed his theory, no distortion had been detected at the surface of Earth (so Earth might have played the role of the grain of sand in our analogy). Something with a mass like our Sun's was necessary to detect the effect Einstein was describing (we will discuss how this effect was measured using the Sun in the next section).

The paperweight in our analogy might be a white dwarf or a neutron star. The distortion of spacetime is greater near the surfaces of these compact, massive objects than near the surface of the Sun. And when, to return to the situation described at the beginning of the chapter, a star core with more than three times the mass of the Sun collapses forever, the distortions of spacetime very close to it can become truly mind-boggling.

### 24.3 Tests of General Relativity

#### Learning Objectives

By the end of this section, you will be able to:

- › Describe unusual motion of Mercury around the Sun and explain how general relativity explains the observed behavior
- › Provide examples of evidence for light rays being bent by massive objects, as predicted by general relativity's theory about the warping of spacetime

What Einstein proposed was nothing less than a major revolution in our understanding of space and time. It was a new theory of gravity, in which mass determines the curvature of spacetime and that curvature, in turn, controls how objects move. Like all new ideas in science, no matter who advances them, Einstein's theory had to be tested by comparing its predictions against the experimental evidence. This was quite a challenge because the effects of the new theory were apparent only when the mass was quite large. (For smaller masses,

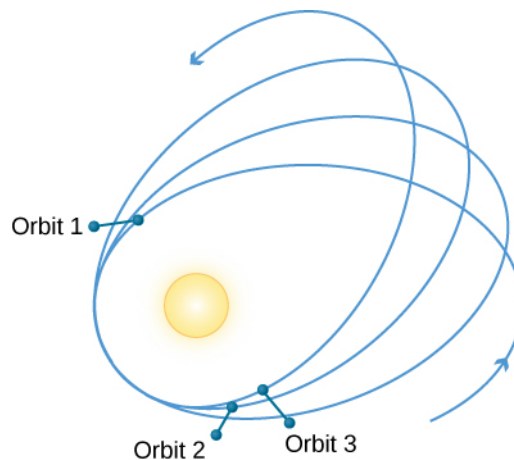
it required measuring techniques that would not become available until decades later.)

When the distorting mass is small, the predictions of general relativity must agree with those resulting from Newton's law of universal gravitation, which, after all, has served us admirably in our technology and in guiding space probes to the other planets. In familiar territory, therefore, the differences between the predictions of the two models are subtle and difficult to detect. Nevertheless, Einstein was able to demonstrate one proof of his theory that could be found in existing data and to suggest another one that would be tested just a few years later.

### The Motion of Mercury

Of the planets in our solar system, Mercury orbits closest to the Sun and is thus most affected by the distortion of spacetime produced by the Sun's mass. Einstein wondered if the distortion might produce a noticeable difference in the motion of Mercury that was not predicted by Newton's law. It turned out that the difference was subtle, but it was definitely there. Most importantly, it had already been measured.

Mercury has a highly elliptical orbit, so that it is only about two-thirds as far from the Sun at perihelion as it is at aphelion. (These terms were defined in the chapter on [Orbits and Gravity](#).) The gravitational effects (perturbations) of the other planets on Mercury produce a calculable advance of Mercury's perihelion. What this means is that each successive perihelion occurs in a slightly different direction as seen from the Sun ([Figure 24.9](#)).



**Figure 24.9 Mercury's Wobble.** The major axis of the orbit of a planet, such as Mercury, rotates in space slightly because of various perturbations. In Mercury's case, the amount of rotation (or orbital precession) is a bit larger than can be accounted for by the gravitational forces exerted by other planets; this difference is precisely explained by the general theory of relativity. Mercury, being the planet closest to the Sun, has its orbit most affected by the warping of spacetime near the Sun. The change from orbit to orbit has been significantly exaggerated on this diagram.

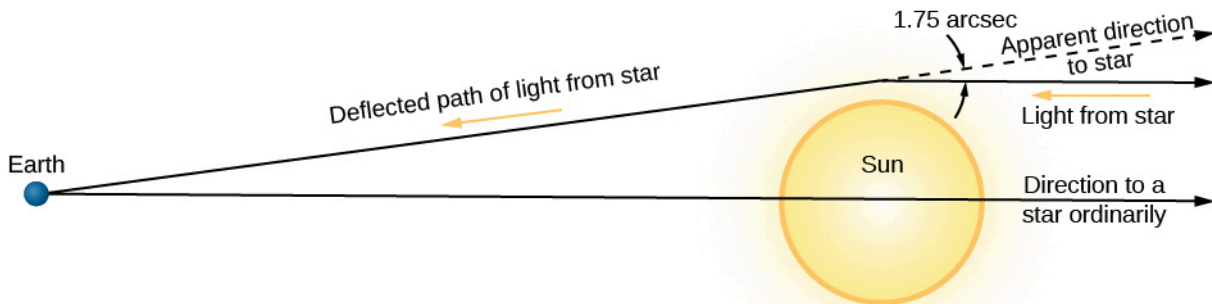
According to Newtonian gravitation, the gravitational forces exerted by the planets will cause Mercury's perihelion to advance by about 531 seconds of arc (arcsec) per century. In the nineteenth century, however, it was observed that the actual advance is 574 arcsec per century. The discrepancy was first pointed out in 1859 by Urbain Le Verrier, the codiscoverer of Neptune. Just as discrepancies in the motion of Uranus allowed astronomers to discover the presence of Neptune, so it was thought that the discrepancy in the motion of Mercury could mean the presence of an undiscovered inner planet. Astronomers searched for this planet near the Sun, even giving it a name: Vulcan, after the Roman god of fire. (The name would later be used for the home planet of a famous character on a popular television show about future space travel.)

But no planet has ever been found nearer to the Sun than Mercury, and the discrepancy was still bothering astronomers when Einstein was doing his calculations. General relativity, however, predicts that due to the curvature of spacetime around the Sun, the perihelion of Mercury should advance slightly more than is predicted by Newtonian gravity. The result is to make the major axis of Mercury's orbit rotate slowly in space because of the Sun's gravity alone. The prediction of general relativity is that the direction of perihelion should

change by an additional 43 arcsec per century. This is remarkably close to the observed discrepancy, and it gave Einstein a lot of confidence as he advanced his theory. The relativistic advance of perihelion was later also observed in the orbits of several asteroids that come close to the Sun.

### Deflection of Starlight

Einstein's second test was something that had not been observed before and would thus provide an excellent confirmation of his theory. Since spacetime is more curved in regions where the gravitational field is strong, we would expect light passing very near the Sun to appear to follow a curved path (Figure 24.10), just like that of the ant in our analogy. Einstein calculated from general relativity theory that starlight just grazing the Sun's surface should be deflected by an angle of 1.75 arcsec. Could such a deflection be observed?



**Figure 24.10 Curvature of Light Paths near the Sun.** Starlight passing near the Sun is deflected slightly by the “warping” of spacetime. (This deflection of starlight is one small example of a phenomenon called gravitational lensing, which we’ll discuss in more detail in [The Evolution and Distribution of Galaxies](#).) Before passing by the Sun, the light from the star was traveling parallel to the bottom edge of the figure. When it passed near the Sun, the path was altered slightly. When we see the light, we assume the light beam has been traveling in a straight path throughout its journey, and so we measure the position of the star to be slightly different from its true position. If we were to observe the star at another time, when the Sun is not in the way, we would measure its true position.

We encounter a small “technical problem” when we try to photograph starlight coming very close to the Sun: the Sun is an outrageously bright source of starlight itself. But during a total solar eclipse, much of the Sun’s light is blocked out, allowing the stars near the Sun to be photographed. In a paper published during World War I, Einstein (writing in a German journal) suggested that photographic observations during an eclipse could reveal the deflection of light passing near the Sun.

The technique involves taking a photograph of the stars six months prior to the eclipse and measuring the position of all the stars accurately. Then the same stars are photographed during the eclipse. This is when the starlight has to travel to us by skirting the Sun and moving through measurably warped spacetime. As seen from Earth, the stars closest to the Sun will seem to be “out of place”—slightly away from their regular positions as measured when the Sun is not nearby.

A single copy of that paper, passed through neutral Holland, reached the British astronomer Arthur S. Eddington, who noted that the next suitable eclipse was on May 29, 1919. The British organized two expeditions to observe it: one on the island of Príncipe, off the coast of West Africa, and the other in Sobral, in northern Brazil. Despite some problems with the weather, both expeditions obtained successful photographs. The stars seen near the Sun were indeed displaced, and to the accuracy of the measurements, which was about 20%, the shifts were consistent with the predictions of general relativity. More modern experiments with radio waves traveling close to the Sun have confirmed that the actual displacements are within 1% of what general relativity predicts.

The confirmation of the theory by the eclipse expeditions in 1919 was a triumph that made Einstein a world celebrity.

## 24.4 Time in General Relativity

### Learning Objectives

By the end of this section, you will be able to:

- › Describe how Einsteinian gravity slows clocks and can decrease a light wave's frequency of oscillation
- › Recognize that the gravitational decrease in a light wave's frequency is compensated by an increase in the light wave's wavelength—the so-called gravitational redshift—so that the light continues to travel at constant speed

General relativity theory makes various predictions about the behavior of space and time. One of these predictions, put in everyday terms, is that *the stronger the gravity, the slower the pace of time*. Such a statement goes very much counter to our intuitive sense of time as a flow that we all share. Time has always seemed the most democratic of concepts: all of us, regardless of wealth or status, appear to move together from the cradle to the grave in the great current of time.

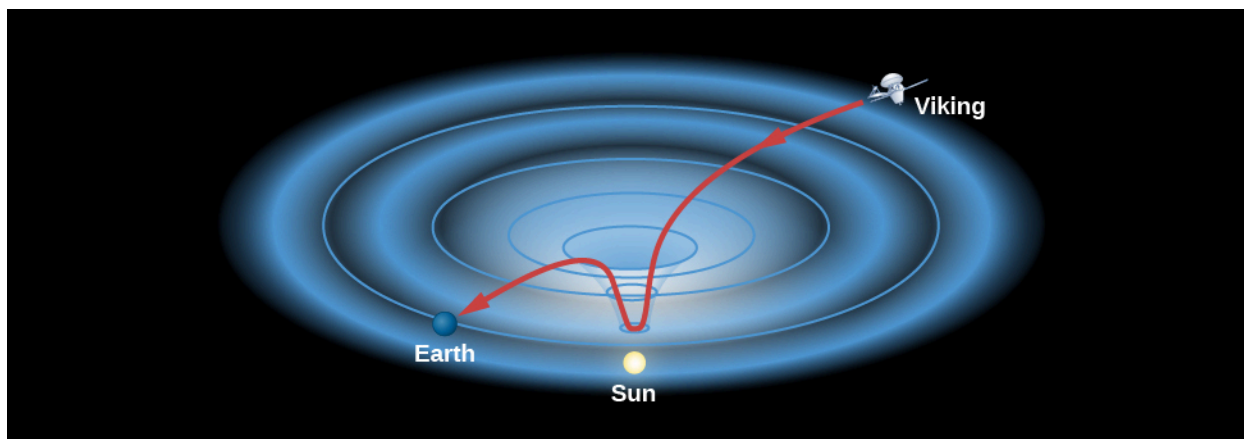
But Einstein argued that it only seems this way to us because all humans so far have lived and died in the gravitational environment of Earth. We have had no chance to test the idea that the pace of time might depend on the strength of gravity, because we have not experienced radically different gravities. Moreover, the differences in the flow of time are extremely small until truly large masses are involved. Nevertheless, Einstein's prediction has now been tested, both on Earth and in space.

### The Tests of Time

An ingenious experiment in 1959 used the most accurate atomic clock known to compare time measurements on the ground floor and the top floor of the physics building at Harvard University. For a clock, the experimenters used the frequency (the number of cycles per second) of gamma rays emitted by radioactive cobalt. Einstein's theory predicts that such a cobalt clock on the ground floor, being a bit closer to Earth's center of gravity, should run very slightly slower than the same clock on the top floor. This is precisely what the experiments observed. Later, atomic clocks were taken up in high-flying aircraft and even on one of the Gemini space flights. In each case, the clocks farther from Earth ran a bit faster. While in 1959 it didn't matter much if the clock at the top of the building ran faster than the clock in the basement, today that effect is highly relevant. Every smartphone or device that synchronizes with a GPS must correct for this (as we will see in the next section) since the clocks on satellites will run faster than clocks on Earth.

The effect is more pronounced if the gravity involved is the Sun's and not Earth's. If stronger gravity slows the pace of time, then it will take longer for a light or radio wave that passes very near the edge of the Sun to reach Earth than we would expect on the basis of Newton's law of gravity. (It takes longer because spacetime is curved in the vicinity of the Sun.) The smaller the distance between the ray of light and the edge of the Sun at closest approach, the longer will be the delay in the arrival time.

In November 1976, when the two Viking spacecraft were operating on the surface of Mars, the planet went behind the Sun as seen from Earth ([Figure 24.11](#)). Scientists had preprogrammed Viking to send a radio wave toward Earth that would go extremely close to the outer regions of the Sun. According to general relativity, there would be a delay because the radio wave would be passing through a region where time ran more slowly. The experiment was able to confirm Einstein's theory to within 0.1%.



**Figure 24.11 Time Delays for Radio Waves near the Sun.** Radio signals from the Viking lander on Mars were delayed when they passed near the Sun, where spacetime is curved relatively strongly. In this picture, spacetime is pictured as a two-dimensional rubber sheet.

### Gravitational Redshift

What does it mean to say that time runs more slowly? When light emerges from a region of strong gravity where time slows down, the light experiences a change in its frequency and wavelength. To understand what happens, let's recall that a wave of light is a repeating phenomenon—crest follows crest with great regularity. In this sense, each light wave is a little clock, keeping time with its wave cycle. If stronger gravity slows down the pace of time (relative to an outside observer), then the rate at which crest follows crest must be correspondingly slower—that is, the waves become less *frequent*.

To maintain constant light speed (the key postulate in Einstein's theories of special and general relativity), the lower frequency must be compensated by a longer wavelength. This kind of increase in wavelength (when caused by the motion of the source) is what we called a *redshift* in [Radiation and Spectra](#). Here, because it is gravity and not motion that produces the longer wavelengths, we call the effect a **gravitational redshift**.

The advent of space-age technology made it possible to measure gravitational redshift with very high accuracy. In the mid-1970s, a hydrogen *maser*, a device akin to a laser that produces a microwave radio signal at a particular wavelength, was carried by a rocket to an altitude of 10,000 kilometers. Instruments on the ground were used to compare the frequency of the signal emitted by the rocket-borne maser with that from a similar maser on Earth. The experiment showed that the stronger gravitational field at Earth's surface really did slow the flow of time relative to that measured by the maser in the rocket. The observed effect matched the predictions of general relativity to within a few parts in 100,000.

These are only a few examples of tests that have confirmed the predictions of general relativity. Today, general relativity is accepted as our best description of gravity and is used by astronomers and physicists to understand the behavior of the centers of galaxies, the beginning of the universe, and the subject with which we began this chapter—the death of truly massive stars.

### Relativity: A Practical Application

By now you may be asking: why should I be bothered with relativity? Can't I live my life perfectly well without it? The answer is you can't. Every time a pilot lands an airplane or you use a GPS to determine where you are on a drive or hike in the back country, you (or at least your GPS-enabled device) must take the effects of both general and special relativity into account.

GPS relies on an array of 24 satellites orbiting the Earth, and at least 4 of them are visible from any spot on Earth. Each satellite carries a precise atomic clock. Your GPS receiver detects the signals from those satellites that are overhead and calculates your position based on the time that it has taken those signals to reach you. Suppose you want to know where you are within 50 feet (GPS devices can actually do much better than this).

Since it takes only 50 billionths of a second for light to travel 50 feet, the clocks on the satellites must be synchronized to at least this accuracy—and relativistic effects must therefore be taken into account.

The clocks on the satellites are orbiting Earth at a speed of 14,000 kilometers per hour and are moving much faster than clocks on the surface of Earth. According to Einstein’s theory of relativity, the clocks on the satellites are ticking more slowly than Earth-based clocks by about 7 millionths of a second per day. (We have not discussed the *special* theory of relativity, which deals with changes when objects move very fast, so you’ll have to take our word for this part.)

The orbits of the satellites are 20,000 kilometers above Earth, where gravity is about four times weaker than at Earth’s surface. General relativity says that the orbiting clocks should tick about 45 millionths of a second faster than they would on Earth. The net effect is that the time on a satellite clock advances by about 38 microseconds per day. If these relativistic effects were not taken into account, navigational errors would start to add up and positions would be off by about 7 miles in only a single day.

## 24.5 Black Holes

### Learning Objectives

By the end of this section, you will be able to:

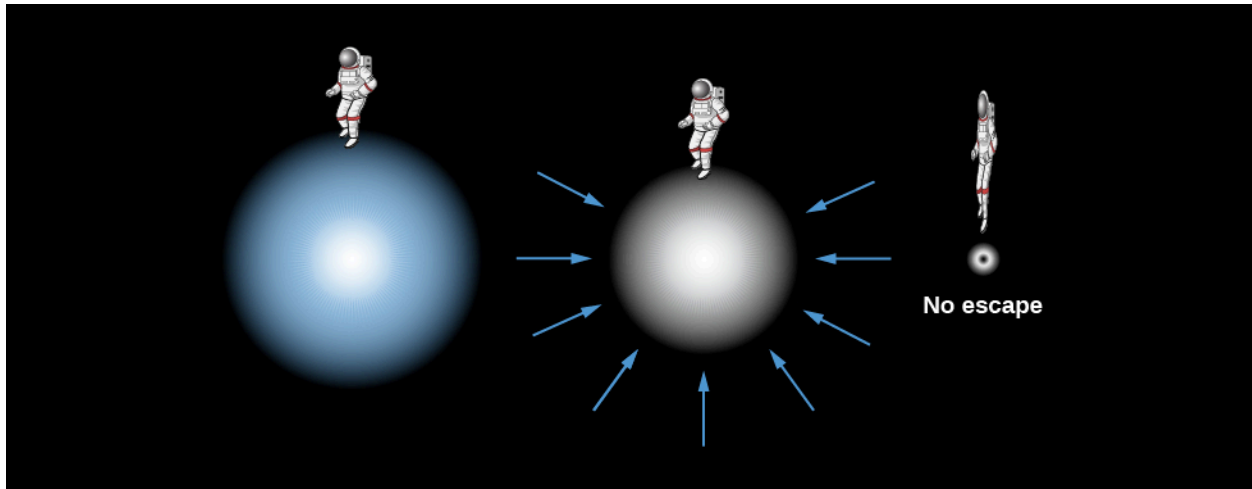
- Explain the event horizon surrounding a black hole
- Discuss why the popular notion of black holes as great sucking monsters that can ingest material at great distances from them is erroneous
- Use the concept of warped spacetime near a black hole to track what happens to any object that might fall into a black hole
- Recognize why the concept of a singularity—with its infinite density and zero volume—presents major challenges to our understanding of matter

Let’s now apply what we have learned about gravity and spacetime curvature to the issue we started with: the collapsing core in a very massive star. We saw that if the core’s mass is greater than about  $3 M_{\text{Sun}}$ , theory says that nothing can stop the core from collapsing forever. We will examine this situation from two perspectives: first from a pre-Einstein point of view, and then with the aid of general relativity.

### Classical Collapse

Let’s begin with a thought experiment. We want to know what speeds are required to escape from the gravitational pull of different objects. A rocket must be launched from the surface of Earth at a very high speed if it is to escape the pull of Earth’s gravity. In fact, any object—rocket, ball, astronomy book—that is thrown into the air with a velocity less than 11 kilometers per second will soon fall back to Earth’s surface. Only those objects launched with a speed greater than this *escape velocity* can get away from Earth.

The escape velocity from the surface of the Sun is higher yet—618 kilometers per second. Now imagine that we begin to compress the Sun, forcing it to shrink in diameter. Recall that the pull of gravity depends on both the mass that is pulling you and your distance from the center of gravity of that mass. If the Sun is compressed, its *mass* will remain the same, but the *distance* between a point on the Sun’s surface and the center will get smaller and smaller. Thus, as we compress the star, the pull of gravity for an object on the shrinking surface will get stronger and stronger ([Figure 24.12](#)).



**Figure 24.12 Formation of a Black Hole.** At left, an imaginary astronaut floats near the surface of a massive star-core about to collapse. As the same mass falls into a smaller sphere, the gravity at its surface goes up, making it harder for anything to escape from the stellar surface. Eventually the mass collapses into so small a sphere that the escape velocity exceeds the speed of light and nothing can get away. Note that the size of the astronaut has been exaggerated. In the last picture, the astronaut is just outside the sphere we will call the event horizon and is stretched and squeezed by the strong gravity.

When the shrinking Sun reaches the diameter of a neutron star (about 20 kilometers), the velocity required to escape its gravitational pull will be about half the speed of light. Suppose we continue to compress the Sun to a smaller and smaller diameter. (We saw this can't happen to a star like our Sun in the real world because of electron degeneracy, i.e., the mutual repulsion between tightly packed electrons; this is just a quick "thought experiment" to get our bearings).

Ultimately, as the Sun shrinks, the escape velocity near the surface would exceed the speed of light. If the speed you need to get away is faster than the fastest possible speed in the universe, then nothing, not even light, is able to escape. An object with such large escape velocity emits no light, and anything that falls into it can never return.

In modern terminology, we call an object from which light cannot escape a **black hole**, a name popularized by the American scientist John Wheeler starting in the late 1960s ([Figure 24.13](#)). The idea that such objects might exist is, however, not a new one. Cambridge professor and amateur astronomer John Michell wrote a paper in 1783 about the possibility that stars with escape velocities exceeding that of light might exist. And in 1796, the French mathematician Pierre-Simon, marquis de Laplace, made similar calculations using Newton's theory of gravity; he called the resulting objects "dark bodies."



**Figure 24.13 John Wheeler (1911–2008).** This brilliant physicist did much pioneering work in general relativity theory and popularized the term *black hole* starting in the late 1960s. (credit: modification of work by Roy Bishop)

While these early calculations provided strong hints that something strange should be expected if very massive objects collapse under their own gravity, we really need general relativity theory to give an adequate description of what happens in such a situation.

### Collapse with Relativity

General relativity tells us that gravity is really a curvature of spacetime. As gravity increases (as in the collapsing Sun of our thought experiment), the curvature gets larger and larger. Eventually, if the Sun could shrink down to a diameter of about 6 kilometers, only light beams sent out perpendicular to the surface would escape. All others would fall back onto the star (Figure 24.14). If the Sun could then shrink just a little more, even that one remaining light beam would no longer be able to escape.



**Figure 24.14 Light Paths near a Massive Object.** Suppose a person could stand on the surface of a normal star with a flashlight. The light leaving the flashlight travels in a straight line no matter where the flashlight is pointed. Now consider what happens if the star collapses so that it is just a little larger than a black hole. All the light paths, except the one straight up, curve back to the surface. When the star shrinks inside the event horizon and becomes a black hole, even a beam directed straight up returns.

Keep in mind that gravity is not pulling on the light. The concentration of matter has curved spacetime, and light (like the trained ant of our earlier example) is “doing its best” to go in a straight line, yet is now confronted with a world in which straight lines that used to go outward have become curved paths that lead back in. The collapsing star is a *black hole* in this view, because the very concept of “out” has no geometrical meaning. The star has become trapped in its own little pocket of spacetime, from which there is no escape.

The star’s geometry cuts off communication with the rest of the universe at precisely the moment when, in our

earlier picture, the escape velocity becomes equal to the speed of light. The size of the star at this moment defines a surface that we call the **event horizon**. It's a wonderfully descriptive name: just as objects that sink below our horizon cannot be seen on Earth, so anything happening inside the event horizon can no longer interact with the rest of the universe.

Imagine a future spacecraft foolish enough to land on the surface of a massive star just as it begins to collapse in the way we have been describing. Perhaps the captain is asleep at the gravity meter, and before the crew can say "Albert Einstein," they have collapsed with the star inside the event horizon. Frantically, they send an escape pod straight outward. But paths outward twist around to become paths inward, and the pod turns around and falls toward the center of the black hole. They send a radio message to their loved ones, bidding good-bye. But radio waves, like light, must travel through spacetime, and curved spacetime allows nothing to get out. Their final message remains unheard. Events inside the event horizon can never again affect events outside it.

The characteristics of an event horizon were first worked out by astronomer and mathematician Karl Schwarzschild (Figure 24.15). A member of the German army in World War I, he died in 1916 of an illness he contracted while doing artillery shell calculations on the Russian front. His paper on the theory of event horizons was among the last things he finished as he was dying; it was the first exact solution to Einstein's equations of general relativity. The radius of the event horizon is called the *Schwarzschild radius* in his memory.



**Figure 24.15 Karl Schwarzschild (1873–1916).** This German scientist was the first to demonstrate mathematically that a black hole is possible and to determine the size of a nonrotating black hole's event horizon.

The event horizon is the boundary of the black hole; calculations show that it does not get smaller once the whole star has collapsed inside it. It is the region that separates the things trapped inside it from the rest of the universe. Anything coming from the outside is also trapped once it comes inside the event horizon. The horizon's size turns out to depend only on the mass inside it. If the Sun, with its mass of  $1 M_{\text{Sun}}$ , were to become a black hole (fortunately, it can't—this is just a thought experiment), the Schwarzschild radius would be about 3 kilometers; thus, the entire black hole would be about one-third the size of a neutron star of that same mass. Feed the black hole some mass, and the horizon will grow—but not very much. Doubling the mass will make the black hole 6 kilometers in radius, still very tiny on the cosmic scale.

The event horizons of more massive black holes have larger radii. For example, if a globular cluster of 100,000 stars (solar masses) could collapse to a black hole, it would be 300,000 kilometers in radius, a little less than half the radius of the Sun. If the entire Galaxy could collapse to a black hole, it would be only about  $10^{12}$  kilometers in radius—about a tenth of a light year. Smaller masses have correspondingly smaller horizons: for Earth to become a black hole, it would have to be compressed to a radius of only 1 centimeter—less than the size of a grape. A typical asteroid, if crushed to a small enough size to be a black hole, would have the

dimensions of an atomic nucleus.

### EXAMPLE 24.1

#### The Milky Way's Black Hole

The size of the event horizon of a black hole depends on the mass of the black hole. The greater the mass, the larger the radius of the event horizon. General relativity calculations show that the formula for the Schwarzschild radius ( $R_S$ ) of the event horizon is

$$R_S = \frac{2GM}{c^2}$$

where  $c$  is the speed of light,  $G$  is the gravitational constant, and  $M$  is the mass of the black hole. Note that in this formula,  $2$ ,  $G$ , and  $c$  are all constant; only the mass changes from black hole to black hole.

As we will see in the chapter on [The Milky Way Galaxy](#), astronomers have traced the paths of several stars near the center of our Galaxy and found that they seem to be orbiting an unseen object—dubbed Sgr A\* (pronounced “Sagittarius A-star”)—with a mass of about 4 million solar masses. What is the size of its Schwarzschild radius?

#### Solution

We can substitute data for  $G$ ,  $M$ , and  $c$  (from [Appendix E](#)) directly into the equation:

$$\begin{aligned} R_S &= \frac{2GM}{c^2} = \frac{2(6.67 \times 10^{-11} \text{ N}\cdot\text{m}^2/\text{kg}^2)(4 \times 10^6)(1.99 \times 10^{30} \text{ kg})}{(3.00 \times 10^8 \text{ m/s})^2} \\ &= 1.18 \times 10^{10} \text{ m} \end{aligned}$$

This distance is about one-fifth of the radius of Mercury's orbit around the Sun, yet the object contains 4 million solar masses and cannot be seen with our largest telescopes. You can see why astronomers are convinced this object is a black hole.

#### Check Your Learning

What would be the size of a black hole that contained only as much mass as a typical pickup truck (about 3000 kg)? (Note that something with so little mass could never actually form a black hole, but it's interesting to think about the result.)

#### Answer:

Substituting the data into our equation gives

$$R_S = \frac{2GM}{c^2} = \frac{2(6.67 \times 10^{-11} \text{ N}\cdot\text{m}^2/\text{kg}^2)(3000 \text{ kg})}{(3.00 \times 10^8 \text{ m/s})^2} = 4.4 \times 10^{-24} \text{ m}.$$

For comparison, the size of a proton is usually considered to be about  $8 \times 10^{-16} \text{ m}$ , which would be about ten million times larger.

### A Black Hole Myth

Much of the modern folklore about black holes is misleading. One idea you may have heard is that black holes go about sucking things up with their gravity. Actually, it is only very close to a black hole that the strange effects we have been discussing come into play. The gravitational attraction far away from a black hole is the same as that of the star that collapsed to form it.

Remember that the gravity of any star some distance away acts as if all its mass were concentrated at a point in the center, which we call the center of gravity. For real stars, we merely *imagine* that all mass is concentrated there; for black holes, all the mass *really is* concentrated at a point in the center.

So, if you are a star or distant planet orbiting around a star that becomes a black hole, your orbit may not be significantly affected by the collapse of the star (although it may be affected by any mass loss that precedes the collapse). If, on the other hand, you venture close to the event horizon, it would be very hard for you to resist the “pull” of the warped spacetime near the black hole. You have to get really close to the black hole to experience any significant effect.

If another star or a spaceship were to pass one or two solar radii from a black hole, Newton’s laws would be adequate to describe what would happen to it. Only very near the event horizon of a black hole is the gravitation so strong that Newton’s laws break down. The black hole remnant of a massive star coming into our neighborhood would be far, far safer to us than its earlier incarnation as a brilliant, hot star.

## MAKING CONNECTIONS



### Gravity and Time Machines

Time machines are one of the favorite devices of science fiction. Such a device would allow you to move through time at a different pace or in a different direction from everyone else. General relativity suggests that it is possible, in theory, to construct a time machine using gravity that could take you into the future.

Let’s imagine a place where gravity is terribly strong, such as near a black hole. General relativity predicts that the stronger the gravity, the slower the pace of time (as seen by a distant observer). So, imagine a future astronaut, with a fast and strongly built spaceship, who volunteers to go on a mission to such a high-gravity environment. The astronaut leaves in the year 2222, just after graduating from college at age 22. She takes, let’s say, exactly 10 years to get to the black hole. Once there, she orbits some distance from it, taking care not to get pulled in.

She is now in a high-gravity realm where time passes much more slowly than it does on Earth. This isn’t just an effect on the mechanism of her clocks—*time itself* is running slowly. That means that every way she has of measuring time will give the same slowed-down reading when compared to time passing on Earth. Her heart will beat more slowly, her hair will grow more slowly, her antique wristwatch will tick more slowly, and so on. She is not aware of this slowing down because all her readings of time, whether made by her own bodily functions or with mechanical equipment, are measuring the same—slower—time. Meanwhile, back on Earth, time passes as it always does.

Our astronaut now emerges from the region of the black hole, her mission of exploration finished, and returns to Earth. Before leaving, she carefully notes that (according to her timepieces) she spent about 2 weeks around the black hole. She then takes exactly 10 years to return to Earth. Her calculations tell her that since she was 22 when she left the Earth, she will be 42 plus 2 weeks when she returns. So, the year on Earth, she figures, should be 2242, and her classmates should now be approaching their midlife crises.

But our astronaut should have paid more attention in her astronomy class! Because time slowed down near the black hole, much less time passed for her than for the people on Earth. While her clocks measured 2 weeks spent near the black hole, more than 2000 weeks (depending on how close she got) could well have passed on Earth. That’s equal to 40 years, meaning her classmates will be senior citizens in their 80s when she (a mere 42-year-old) returns. On Earth it will be not 2242, but 2282—and she will say that she has arrived *in the future*.

Is this scenario real? Well, it has a few practical challenges: we don’t think any black holes are close enough for us to reach in 10 years, and we don’t think any spaceship or human can survive near a black hole. But the key point about the slowing down of time is a natural consequence of Einstein’s general theory of relativity, and we saw that its predictions have been confirmed by experiment after experiment.

Such developments in the understanding of science also become inspiration for science fiction writers. Recently, the film *Interstellar* featured the protagonist traveling close to a massive black hole; the resulting delay in his aging relative to his earthbound family is a key part of the plot.

Science fiction novels, such as *Gateway* by Frederik Pohl and *A World out of Time* by Larry Niven, also make use of the slowing down of time near black holes as major turning points in the story. For a list of science fiction stories based on good astronomy, you can go to <http://bit.ly/astroscifi> (<http://bit.ly/astroscifi>).

## A Trip into a Black Hole

The fact that scientists cannot see inside black holes has not kept them from trying to calculate what they are like. One of the first things these calculations showed was that the formation of a black hole obliterates nearly all information about the star that collapsed to form it. Physicists like to say “black holes have no hair,” meaning that nothing sticks out of a black hole to give us clues about what kind of star produced it or what material has fallen inside. The only information a black hole can reveal about itself is its mass, its spin (rotation), and whether it has any electrical charge.

What happens to the collapsing star-core that made the black hole? Our best calculations predict that the material will continue to collapse under its own weight, forming an infinitely *squozed* point—a place of zero volume and infinite density—to which we give the name **singularity**. At the singularity, spacetime ceases to exist. The laws of physics as we know them break down. We do not yet have the physical understanding or the mathematical tools to describe the singularity itself, or even if singularities actually occur. From the outside, however, the entire structure of a basic black hole (one that is not rotating) can be described as a singularity surrounded by an event horizon. Compared to humans, black holes are really very simple objects.

Scientists have also calculated what would happen if an astronaut were to fall into a black hole. Let’s take up an observing position a long, safe distance away from the event horizon and watch this astronaut fall toward it. At first he falls away from us, moving ever faster, just as though he were approaching any massive star. However, as he nears the event horizon of the black hole, things change. The strong gravitational field around the black hole will make his clocks run more slowly, when seen from our outside perspective.

If, as he approaches the event horizon, he sends out a signal once per second according to his clock, we will see the spacing between his signals grow longer and longer until it becomes infinitely long when he reaches the event horizon. (Recalling our discussion of gravitational redshift, we could say that if the infalling astronaut uses a blue light to send his signals every second, we will see the light get redder and redder until its wavelength is nearly infinite.) As the spacing between clock ticks approaches infinity, it will appear to us that the astronaut is slowly coming to a stop, frozen in time at the event horizon.

In the same way, all matter falling into a black hole will also appear to an outside observer to stop at the event horizon, frozen in place and taking an infinite time to fall through it. But don’t think that matter falling into a black hole will therefore be easily visible at the event horizon. The tremendous redshift will make it very difficult to observe any radiation from the “frozen” victims of the black hole.

This, however, is only how we, located far away from the black hole, see things. To the astronaut, his time goes at its normal rate and he falls right on through the event horizon into the black hole. (Remember, this horizon is not a physical barrier, but only a region in space where the curvature of spacetime makes escape impossible.)

You may have trouble with the idea that you (watching from far away) and the astronaut (falling in) have such different ideas about what has happened. This is the reason Einstein’s ideas about space and time are called theories of *relativity*. What each observer measures about the world depends on (is relative to) his or her frame of reference. The observer in strong gravity measures time and space differently from the one sitting in weaker gravity. When Einstein proposed these ideas, many scientists also had difficulty with the idea that two

such different views of the same event could be correct, each in its own “world,” and they tried to find a mistake in the calculations. There were no mistakes: we and the astronaut really would see him fall into a black hole very differently.

For the astronaut, there is no turning back. Once inside the event horizon, the astronaut, along with any signals from his radio transmitter, will remain hidden forever from the universe outside. He will, however, not have a long time (from his perspective) to feel sorry for himself as he approaches the black hole. Suppose he is falling feet first. The force of gravity that the singularity exerts on his feet is greater than on his head, so he will be stretched slightly. Because the singularity is a point, the left side of his body will be pulled slightly toward the right, and the right slightly toward the left, bringing each side closer to the singularity. The astronaut will therefore be slightly squeezed in one direction and stretched in the other. Some scientists like to call this process of stretching and narrowing *spaghettification*. The point at which the astronaut becomes so stretched that he perishes depends on the size of the black hole. For black holes with masses billions of times the mass of the Sun, such as those found at the centers of galaxies, the spaghettification becomes significant only after the astronaut passes through the event horizon. For black holes with masses of a few solar masses, the astronaut will be stretched and ripped apart even before he reaches the event horizon.

Earth exerts similar *tidal forces* on an astronaut performing a spacewalk. In the case of Earth, the tidal forces are so small that they pose no threat to the health and safety of the astronaut. Not so in the case of a black hole. Sooner or later, as the astronaut approaches the black hole, the tidal forces will become so great that the astronaut will be ripped apart, eventually reduced to a collection of individual atoms that will continue their inexorable fall into the singularity.

### LINK TO LEARNING



From the previous discussion, you will probably agree that jumping into a black hole is definitely a once-in-a-lifetime experience! You can see an [engaging explanation \(https://openstax.org/l/30ndegtystidfor\)](https://openstax.org/l/30ndegtystidfor) of death by black hole by Neil deGrasse Tyson, where he explains the effect of tidal forces on the human body until it dies by spaghettification.

An overview of black holes is given in this [Discovery Channel video \(https://openstax.org/l/30dischatidfor\)](https://openstax.org/l/30dischatidfor) excerpt.

## 24.6 Evidence for Black Holes

### Learning Objectives

By the end of this section, you will be able to:

- Describe what to look for when seeking and confirming the presence of a stellar black hole
- Explain how a black hole is inherently black yet can be associated with luminous matter
- Differentiate between stellar black holes and the black holes in the centers of galaxies

Theory tells us what black holes are like. But do they actually exist? And how do we go about looking for something that is many light years away, only about a few dozen kilometers across (if a stellar black hole), and completely black? It turns out that the trick is not to look for the black hole itself but instead to look for what it does to a nearby companion star.

As we saw, when very massive stars collapse, they leave behind their gravitational influence. What if a member of a double-star system becomes a black hole, and its companion manages to survive the death of the massive star? While the black hole disappears from our view, we may be able to deduce its presence from the things it does to its companion.

## Requirements for a Black Hole

So, here is a prescription for finding a black hole: start by looking for a star whose motion (determined from the Doppler shift of its spectral lines) shows it to be a member of a binary star system. If both stars are visible, neither can be a black hole, so focus your attention on just those systems where only one star of the pair is visible, even with our most sensitive telescopes.

Being invisible is not enough, however, because a relatively faint star might be hard to see next to the glare of a brilliant companion or if it is shrouded by dust. And even if the star really is invisible, it could be a neutron star. Therefore, we must also have evidence that the unseen star has a mass too high to be a neutron star and that it is a collapsed object—an extremely small stellar remnant.

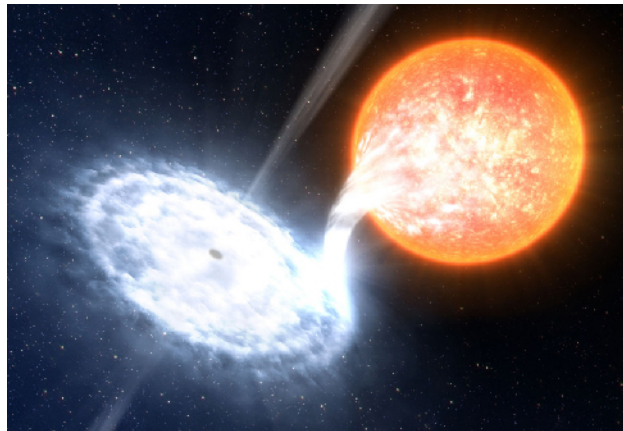
We can use Kepler's law (see [Orbits and Gravity](#)) and our knowledge of the visible star to measure the mass of the invisible member of the pair. If the mass is greater than about  $3 M_{\text{Sun}}$ , then we are likely seeing (or, more precisely, not seeing) a black hole—as long as we can make sure the object really is a collapsed star.

If matter falls toward a compact object of high gravity, the material is accelerated to high speed. Near the event horizon of a black hole, matter is moving at velocities that approach the speed of light. As the atoms whirl chaotically toward the event horizon, they rub against each other; internal friction can heat them to temperatures of 100 million K or more. Such hot matter emits radiation in the form of flickering X-rays. The last part of our prescription, then, is to look for a source of X-rays associated with the binary system. Since X-rays do not penetrate Earth's atmosphere, such sources must be found using X-ray telescopes in space.

In our example, the infalling gas that produces the X-ray emission comes from the black hole's companion star. As we saw in [The Death of Stars](#), stars in close binary systems can exchange mass, especially as one of the members expands into a red giant. Suppose that one star in a double-star system has evolved to a black hole and that the second star begins to expand. If the two stars are not too far apart, the outer layers of the expanding star may reach the point where the black hole exerts more gravitational force on them than do the inner layers of the red giant to which the atmosphere belongs. The outer atmosphere then passes through the point of no return between the stars and falls toward the black hole.

The mutual revolution of the giant star and the black hole causes the material falling toward the black hole to spiral around it rather than flow directly into it. The infalling gas whirls around the black hole in a pancake of matter called an **accretion disk**. It is within the inner part of this disk that matter is revolving about the black hole so fast that internal friction heats it up to X-ray-emitting temperatures (see [Figure 24.1](#)).

Another way to form an accretion disk in a binary star system is to have a powerful stellar wind come from the black hole's companion. Such winds are a characteristic of several stages in a star's life. Some of the ejected gas in the wind will then flow close enough to the black hole to be captured by it into the disk ([Figure 24.16](#)).



**Figure 24.16 Binary Black Hole.** This artist's rendition shows a black hole and star (red). As matter streams from the star, it forms a disk around the black hole. Some of the swirling material close to the black hole is pushed outward perpendicular to the disk in two narrow jets. (credit: modification of work by ESO/L. Calçada)

We should point out that, as often happens, the measurements we have been discussing are not quite as simple as they are described in introductory textbooks. In real life, Kepler's law allows us to calculate only the combined mass of the two stars in the binary system. We must learn more about the visible star of the pair and its history to ascertain the distance to the binary pair, the true size of the visible star's orbit, and how the orbit of the two stars is tilted toward Earth, something we can rarely measure. And neutron stars can also have accretion disks that produce X-rays, so astronomers must study the properties of these X-rays carefully when trying to determine what kind of object is at the center of the disk. Nevertheless, a number of systems that clearly contain black holes have now been found.

### The Discovery of Stellar-Mass Black Holes

Because X-rays are such important tracers of black holes that are having some of their stellar companions for lunch, the search for black holes had to await the launch of sophisticated X-ray telescopes into space. These instruments must have the resolution to locate the X-ray sources accurately and thereby enable us to match them to the positions of binary star systems.

The first black hole binary system to be discovered is called Cygnus X-1 (see [Figure 24.1](#)). The visible star in this binary system is spectral type O. Measurements of the Doppler shifts of the O star's spectral lines show that it has an unseen companion. The X-rays flickering from it strongly indicate that the companion is a small collapsed object. The mass of the invisible collapsed companion is about 15 times that of the Sun. The companion is therefore too massive to be either a white dwarf or a neutron star.

A number of other binary systems also meet all the conditions for containing a black hole. [Table 24.1](#) lists the characteristics of some of the best examples.

**Some Black Hole Candidates in Binary Star Systems**

Name/Catalog Designation <sup>2</sup>	Companion Star Spectral Type	Orbital Period (days)	Black Hole Mass Estimates ( $M_{\text{Sun}}$ )
LMC X-1	O giant	3.9	10.9
Cygnus X-1	O supergiant	5.6	15
XTE J1819.3-254 (V4641 Sgr)	B giant	2.8	6–7
LMC X-3	B main sequence	1.7	7
4U1543-475 (IL Lup)	A main sequence	1.1	9
GRO J1655-40 (V1033 Sco)	F subgiant	2.6	7
GRS 1915+105	K giant	33.5	14
GS202+1338 (V404 Cyg)	K giant	6.5	12
XTE J1550-564	K giant	1.5	11
A0620-00 (V616 Mon)	K main sequence	0.33	9–13

**Table 24.1**

Name/Catalog Designation <sup>2</sup>	Companion Star Spectral Type	Orbital Period (days)	Black Hole Mass Estimates ( $M_{\text{Sun}}$ )
H1705-250 (Nova Oph 1977)	K main sequence	0.52	5–7
GRS1124-683 (Nova Mus 1991)	K main sequence	0.43	7
GS2000+25 (QZ Vul)	K main sequence	0.35	5–10
GRS1009-45 (Nova Vel 1993)	K dwarf	0.29	8–9
XTE J1118+480	K dwarf	0.17	7
XTE J1859+226	K dwarf	0.38	5.4
GRO J0422+32	M dwarf	0.21	4

Table 24.1

## Feeding a Black Hole

After an isolated star, or even one in a binary star system, becomes a black hole, it probably won't be able to grow much larger. Out in the suburban regions of the Milky Way Galaxy where we live (see [The Milky Way Galaxy](#)), stars and star systems are much too far apart for other stars to provide “food” to a hungry black hole. After all, material must approach very close to the event horizon before the gravity is any different from that of the star before it became the black hole.

But, as will see, the central regions of galaxies are quite different from their outer parts. Here, stars and raw material can be quite crowded together, and they can interact much more frequently with each other. Therefore, black holes in the centers of galaxies may have a much better opportunity to find mass close enough to their event horizons to pull in. Black holes are not particular about what they “eat”: they are happy to consume other stars, asteroids, gas, dust, and even other black holes. (If two black holes merge, you just get a black hole with more mass and a larger event horizon.)

As a result, black holes in crowded regions can grow, eventually swallowing thousands or even millions of times the mass of the Sun. Ground-based observations have provided compelling evidence that there is a black hole in the center of our own Galaxy with a mass of about 4 million times the mass of the Sun (we'll discuss this further in the chapter on [The Milky Way Galaxy](#)). Observations with the Hubble Space Telescope have shown dramatic evidence for the existence of black holes in the centers of many other galaxies. These black holes can contain more than a billion solar masses. The feeding frenzy of such supermassive black holes may be responsible for some of the most energetic phenomena in the universe (see [Active Galaxies, Quasars, and Supermassive Black Holes](#)). And evidence from more recent X-ray observations is also starting to indicate the existence of “middle-weight” black holes, whose masses are dozens to thousands of times the mass of the Sun. The crowded inner regions of the globular clusters we described in [Stars from Adolescence to Old Age](#) may be just the right breeding grounds for such intermediate-mass black holes.

Over the past decades, many observations, especially with the Hubble Space Telescope and with X-ray

<sup>2</sup> As you can tell, there is no standard way of naming these candidates. The chain of numbers is the location of the source in right ascension and declination (the longitude and latitude system of the sky); some of the letters preceding the numbers refer to objects (e.g., LMC) and constellations (e.g., Cygnus), while other letters refer to the satellite that discovered the candidate—A for Ariel, G for Ginga, and so on. The notations in parentheses are those used by astronomers who study binary star system or novae.

satellites, have been made that can be explained only if black holes really do exist. Furthermore, the observational tests of Einstein's general theory of relativity have convinced even the most skeptical scientists that his picture of warped or curved spacetime is indeed our best description of the effects of gravity near these black holes.

## 24.7 Gravitational Wave Astronomy

### Learning Objectives

By the end of this section, you will be able to:

- › Describe what a gravitational wave is, what can produce it, and how fast it propagates
- › Understand the basic mechanisms used to detect gravitational waves

Another part of Einstein's ideas about gravity can be tested as a way of checking the theory that underlies black holes. According to general relativity, the geometry of spacetime depends on where matter is located. Any rearrangement of matter—say, from a sphere to a sausage shape—creates a disturbance in spacetime. This disturbance is called a **gravitational wave**, and relativity predicts that it should spread outward at the speed of light. The big problem with trying to study such waves is that they are tremendously weaker than electromagnetic waves and correspondingly difficult to detect.

### Proof from a Pulsar

We've had indirect evidence for some time that gravitational waves exist. In 1974, astronomers Joseph Taylor and Russell Hulse discovered a pulsar (with the designation PSR1913+16) orbiting another neutron star. Pulled by the powerful gravity of its companion, the pulsar is moving at about one-tenth the speed of light in its orbit.

According to general relativity, this system of stellar corpses should be radiating energy in the form of gravitational waves at a high enough rate to cause the pulsar and its companion to spiral closer together. If this is correct, then the orbital period should decrease (according to Kepler's third law) by one ten-millionth of a second per orbit. Continuing observations showed that the period is decreasing by precisely this amount. Such a loss of energy in the system can be due only to the radiation of gravitational waves, thus confirming their existence. Taylor and Hulse shared the 1993 Nobel Prize in physics for this work.

### Direct Observations

Although such an indirect proof convinced physicists that gravitational waves exist, it is even more satisfying to detect the waves directly. What we need are phenomena that are powerful enough to produce gravitational waves with amplitudes large enough that we can measure them. Theoretical calculations suggest some of the most likely events that would give a burst of gravitational waves strong enough that our equipment on Earth could measure it:

- the coalescence of two neutron stars in a binary system that spiral together until they merge
- the swallowing of a neutron star by a black hole
- the coalescence (merger) of two black holes
- the implosion of a really massive star to form a neutron star or a black hole
- the first "shudder" when space and time came into existence and the universe began

For the last four decades, scientists have been developing an audacious experiment to try to detect gravitational waves from a source on this list. The US experiment, which was built with collaborators from the UK, Germany, Australia and other countries, is named LIGO (Laser Interferometer Gravitational-Wave Observatory). LIGO currently has two observing stations, one in Louisiana and the other in the state of Washington. The effects of gravitational waves are so small that confirmation of their detection will require simultaneous measurements by two widely separated facilities. Local events that might cause small motions within the observing stations and mimic gravitational waves—such as small earthquakes, ocean tides, and even traffic—should affect the two sites differently.

Each of the LIGO stations consists of two 4-kilometer-long, 1.2-meter-diameter vacuum pipes arranged in an L-shape. A test mass with a mirror on it is suspended by wire at each of the four ends of the pipes. Ultra-stable laser light is reflected from the mirrors and travels back and forth along the vacuum pipes (Figure 24.17). If gravitational waves pass through the LIGO instrument, then, according to Einstein's theory, the waves will affect local spacetime—they will alternately stretch and shrink the distance the laser light must travel between the mirrors ever so slightly. When one arm of the instrument gets longer, the other will get shorter, and vice versa.



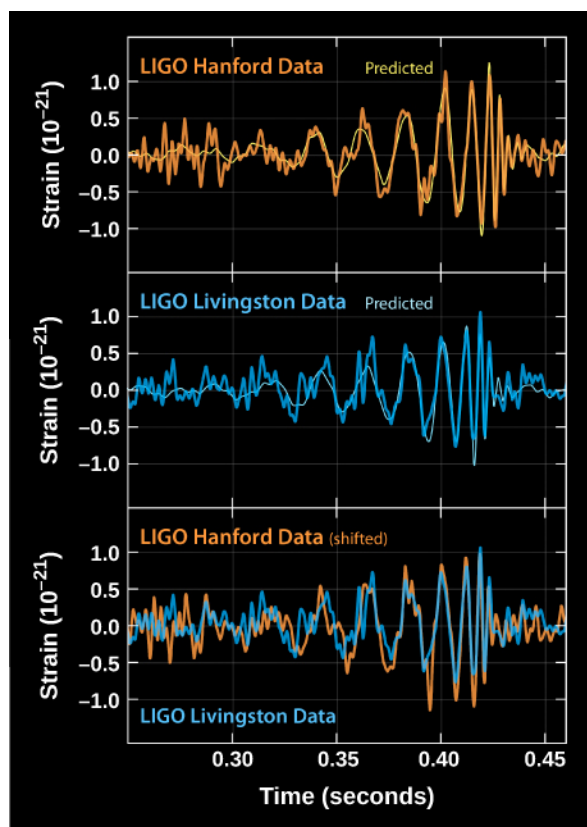
**Figure 24.17 Gravitational Wave Telescope.** An aerial view of the LIGO facility at Livingston, Louisiana. Extending to the upper left and far right of the image are the 4-kilometer-long detectors. (credit: modification of work by Caltech/MIT/LIGO Laboratory)

The challenge of this experiment lies in that phrase “ever so slightly.” In fact, to detect a gravitational wave, the change in the distance to the mirror must be measured with an accuracy of *one ten-thousandth the diameter of a proton*. In 1972, Rainer Weiss of MIT wrote a paper suggesting how this seemingly impossible task might be accomplished.

A great deal of new technology had to be developed, and work on the laboratory, with funding from the National Science Foundation, began in 1979. A full-scale prototype to demonstrate the technology was built and operated from 2002 to 2010, but the prototype was not expected to have the sensitivity required to actually detect gravitational waves from an astronomical source. Advanced LIGO, built to be more precise with the improved technology developed in the prototype, went into operation in 2015—and almost immediately detected gravitational waves.

What LIGO found was gravitational waves produced in the final fraction of a second of the merger of two black holes (Figure 24.18). The black holes had masses of 20 and 36 times the mass of the Sun, and the merger took place 1.3 billion years ago—the gravitational waves occurred so far away that it has taken that long for them, traveling at the speed of light, to reach us.

In the cataclysm of the merger, about three times the mass of the Sun was converted to energy (recall  $E = mc^2$ ). During the tiny fraction of a second for the merger to take place, this event produced power about 10 times the power produced by all the stars in the entire visible universe—but the power was all in the form of gravitational waves and hence was invisible to our instruments, except to LIGO. The event was recorded in Louisiana about 7 milliseconds before the detection in Washington—just the right distance given the speed at which gravitational waves travel—and indicates that the source was located somewhere in the southern hemisphere sky. Unfortunately, the merger of two black holes is not expected to produce any light, so this is the only observation we have of the event.



(a)



(b)

**Figure 24.18 Signal Produced by a Gravitational Wave.** (a) The top panel shows the signal measured at Hanford, Washington; the middle panel shows the signal measured at Livingston, Louisiana. The smoother thin curve in each panel shows the predicted signal, based on Einstein's general theory of relativity, produced by the merger of two black holes. The bottom panel shows a superposition of the waves detected at the two LIGO observatories. Note the remarkable agreement of the two independent observations and of the observations with theory. (b) The painting shows an artist's impression of two massive black holes spiraling inward toward an eventual merger. (credit a, b: modification of work by SXS)

This detection by LIGO (and another one of a different black hole merger a few months later) opened a whole new window on the universe. One of the experimenters compared the beginning of gravitational wave astronomy to the era when silent films were replaced by movies with sound (comparing the vibration of spacetime during the passing of a gravitational wave to the vibrations that sound makes).

By the end of 2021, the LIGO-Virgo collaboration (Virgo is a gravitational wave detector operated by the European Gravitational Observatory in Italy) published a catalog that now included some 90 events. Most were mergers of two black holes, and most involved black holes with a range of masses detected only by gravitational waves (see [Figure 24.19](#)). In the most extreme merger, black holes with masses of 86 and 65 times the mass of the Sun merged to form a black hole with a mass of about 142 times the mass the Sun, and released energy equivalent to 9 times the mass of our Sun (remember  $E=mc^2$ )—an enormous amount.

Astronomers are not yet sure how black holes in this unexpected mass range form. Bear in mind that the kind of black holes in binary star systems that we discussed in [Evidence for Black Holes](#) (and listed in [Table 24.1](#)) have masses ranging from 4 to 15 times the mass of the Sun.

To be sure, a few mergers did involve black holes with stellar masses comparable to those of black holes in X-ray binary systems. In one case, for example, the merging black holes had masses of 14 and 8 times the mass of the Sun.

While astronomers can learn about the masses of objects involved in gravitational wave events, the challenge is to locate the event in the sky precisely. A single gravitational wave detector cannot determine accurately the direction to a gravitational wave source. Four comparable detectors operating simultaneously are required to

localize a source of gravitational waves *in every location* in the sky. The first observing run with four detectors, including the two LIGO detectors, Virgo, and KAGRA in Japan, is scheduled to begin in the summer of 2022. LIGO India will be a fifth, thereby enhancing the probability that at least four detectors will be operational simultaneously. Experience has shown that the LIGO and Virgo detectors are down about 25 percent of the time because these complex systems are difficult to run.

A three-observatory network does provide a sharp location for events that occur in about half of all possible locations on the sky.

In late 2017, data from the LIGO and Virgo detectors provided an accurate position for what analysis showed was the spiraling together of two neutron stars with masses of 1.1 to 1.6 times the mass of the Sun (see [The Death of Stars](#)).

With an accurate location known, follow up observations with ground-based telescopes detected electromagnetic emission from a gravitational wave event for the first time. The observations showed that this source was located in NGC 4993, a galaxy at a distance of about 130 million light-years in the direction of the constellation Hydra. The Fermi satellite detected a flash of gamma rays at the same time and in the same direction, which confirms the long-standing hypothesis that mergers of neutron stars are progenitors of short gamma-ray bursts (see [The Mystery of Gamma-Ray Bursts](#)). Spectra showed that the merger ejected material with a mass of about 6 percent of the mass of the Sun at a speed of one-tenth the speed of light.

This material is rich in heavy elements, just as the theory of kilonovas (see [The Mystery of Gamma-Ray Bursts](#)) predicted. First estimates suggest that the merger produced about 200 Earth masses of gold, and around 500 Earth masses of platinum. This makes clear that neutron star mergers are a significant source of heavy elements. More such mergers are being found (see [Figure 24.19](#)) and they will improve estimates of the frequency at which neutron star mergers occur; it may well turn out that the vast majority of heavy elements have been created in such cataclysms.

No electromagnetic observations have been detected from the mergers of two black holes.

In June 2021, scientists from LIGO and Virgo announced the first detection of mergers between black holes and neutron stars, another of the really energetic events that we listed as possible sources for a detectable burst of gravitational waves. Again, no electromagnetic waves from the two events were observed or expected, demonstrating the importance of using what we are now calling “multi-messenger astronomy” to understand the universe fully.

Observing the merger of black holes via gravitational waves means that we can now test Einstein’s general theory of relativity where its effects are very strong—close to black holes—and not weak, as they are near Earth. One remarkable result from these detections is that the observed signals so closely match the theoretical predictions made using Einstein’s theory. Once again, Einstein’s revolutionary idea is found to be the correct description of nature.

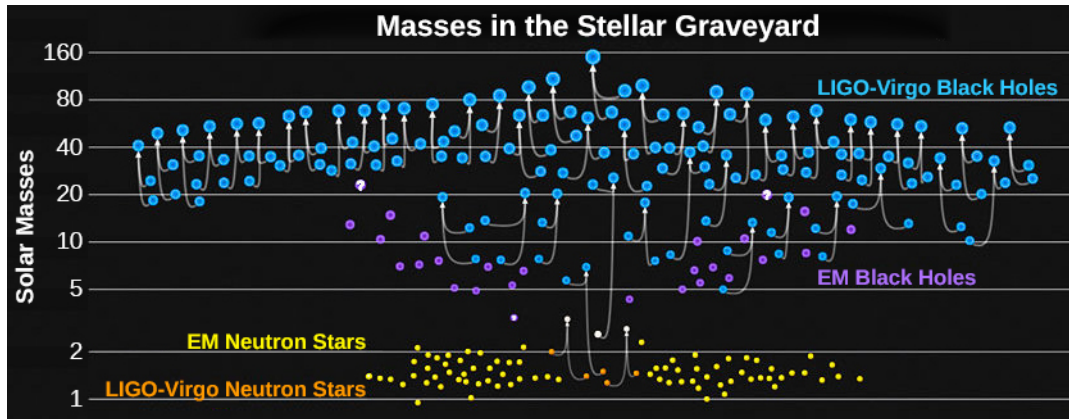
Because of the scientific significance of the observations of gravitational waves, three of the LIGO project leaders—Rainer Weiss of MIT, and Kip Thorne and Barry Barish of Caltech—were awarded the Nobel Prize in 2017.

Ground-based gravitational-wave detectors can detect mergers of black holes with masses up to about 100 times the mass of the Sun. Astronomers would now like to look for the merger of distant supermassive black holes (see [Supermassive Black Holes: What Quasars Really Are](#)) with masses of thousands to millions of times larger, which might have occurred when the first generation of stars formed, only a few hundred million years after the Big Bang. The gravitational waves emitted by mergers of supermassive black holes are so long that it is necessary to go to space to build an observatory large enough to detect them.

ESA (the European Space Agency), with contributions from NASA, is planning to launch a facility named LISA (Laser Interferometer Space Antenna) in 2034 to search for mergers of black holes with masses thousands to

millions of times larger than the mass of the Sun. The experiment will consist of three spacecraft arranged in an equilateral triangle with sides 2.5 million km long, flying along an Earth-like heliocentric orbit. A test mass floats free inside each spacecraft, effectively in free-fall, while the spacecraft around it absorbs the effects of light pressure, solar wind particles, and anything that might perturb its orbit. Lasers will be used to measure very accurately the distances between the test masses. Changes in distance will then signal the passing of gravitational waves.

We should end by acknowledging that the ideas discussed in this chapter may seem strange and overwhelming, especially the first time you read them. The consequences of the general theory of relativity take some getting used to. But they make the universe more bizarre—and interesting—than you probably thought before you took this course.



**Figure 24.19 Some Black Hole Merger Events Observed with Gravitational Waves.** The vertical axis shows the masses for some known black holes and neutron stars. The light blue dots represent black hole mergers seen with LIGO-Virgo, with the individual black holes and the resulting merged black hole connected with an arrow. Note that, as a result of these mergers, we are starting to observe some black holes with masses so large that new ideas may be required to explain them. The purple dots represent black holes seen with electro-magnetic radiation; these have significantly smaller masses. The orange dots represent neutron star mergers seen through the gravitational waves they emit. The yellow dots are neutron stars seen with electro-magnetic radiation. (credit: courtesy Caltech/MIT/LIGO Laboratory; LIGO-Virgo/Frank Elavsky, Aaron Geller/Northwestern)

## Key Terms

**accretion disk** the disk of gas and dust found orbiting newborn stars, as well as compact stellar remnants such as white dwarfs, neutron stars, and black holes when they are in binary systems and are sufficiently close to their binary companions to draw off material

**black hole** a region in spacetime where gravity is so strong that nothing—not even light—can escape

**equivalence principle** concept that a gravitational force and a suitable acceleration are indistinguishable within a sufficiently local environment

**event horizon** a boundary in spacetime such that events inside the boundary can have no effect on the world outside it—that is, the boundary of the region around a black hole where the curvature of spacetime no longer provides any way out

**general theory of relativity** Einstein's theory relating gravity and the structure (geometry) of space and time

**gravitational redshift** an increase in wavelength of an electromagnetic wave (light) when propagating from or near a massive object

**gravitational wave** a disturbance in the curvature of spacetime caused by changes in how matter is distributed; gravitational waves propagate at (or near) the speed of light.

**singularity** the point of zero volume and infinite density to which any object that becomes a black hole must collapse, according to the theory of general relativity

**spacetime** system of one time and three space coordinates, with respect to which the time and place of an event can be specified

## Summary

### [24.1 Introducing General Relativity](#)

Einstein proposed the equivalence principle as the foundation of the theory of general relativity. According to this principle, there is no way that anyone or any experiment in a sealed environment can distinguish between free fall and the absence of gravity.

### [24.2 Spacetime and Gravity](#)

By considering the consequences of the equivalence principle, Einstein concluded that we live in a curved spacetime. The distribution of matter determines the curvature of spacetime; other objects (and even light) entering a region of spacetime must follow its curvature. Light must change its path near a massive object not because light is bent by gravity, but because spacetime is.

### [24.3 Tests of General Relativity](#)

In weak gravitational fields, the predictions of general relativity agree with the predictions of Newton's law of gravity. However, in the stronger gravity of the Sun, general relativity makes predictions that differ from Newtonian physics and can be tested. For example, general relativity predicts that light or radio waves will be deflected when they pass near the Sun, and that the position where Mercury is at perihelion would change by 43 arcsec per century even if there were no other planets in the solar system to perturb its orbit. These predictions have been verified by observation.

### [24.4 Time in General Relativity](#)

General relativity predicts that the stronger the gravity, the more slowly time must run. Experiments on Earth and with spacecraft have confirmed this prediction with remarkable accuracy. When light or other radiation emerges from a compact smaller remnant, such as a white dwarf or neutron star, it shows a gravitational redshift due to the slowing of time.

## 24.5 Black Holes

Theory suggests that stars with stellar cores more massive than three times the mass of the Sun at the time they exhaust their nuclear fuel will collapse to become black holes. The surface surrounding a black hole, where the escape velocity equals the speed of light, is called the event horizon, and the radius of the surface is called the Schwarzschild radius. Nothing, not even light, can escape through the event horizon from the black hole. At its center, each black hole is thought to have a singularity, a point of infinite density and zero volume. Matter falling into a black hole appears, as viewed by an outside observer, to freeze in position at the event horizon. However, if we were riding on the infalling matter, we would pass through the event horizon. As we approach the singularity, the tidal forces would tear our bodies apart even before we reach the singularity.

## 24.6 Evidence for Black Holes

The best evidence of stellar-mass black holes comes from binary star systems in which (1) one star of the pair is not visible, (2) the flickering X-ray emission is characteristic of an accretion disk around a compact object, and (3) the orbit and characteristics of the visible star indicate that the mass of its invisible companion is greater than  $3 M_{\text{Sun}}$ . A number of systems with these characteristics have been found. Black holes with masses of millions to billions of solar masses are found in the centers of large galaxies.

## 24.7 Gravitational Wave Astronomy

General relativity predicts that the rearrangement of matter in space should produce gravitational waves. The existence of such waves was first confirmed in observations of a pulsar in orbit around another neutron star whose orbits were spiraling closer and losing energy in the form of gravitational waves. In 2015, LIGO found gravitational waves directly by detecting the signal produced by the merger of two stellar-mass black holes, opening a new window on the universe. Since then, many other gravitational wave signals have been found, signaling the mergers of both black holes and neutron stars.



### For Further Exploration

#### Articles

##### **Black Holes**

Charles, P. & Wagner, R. "Black Holes in Binary Stars: Weighing the Evidence." *Sky & Telescope* (May 1996): 38. Excellent review of how we find stellar-mass black holes.

Gezari, S. "Star-Shredding Black Holes." *Sky & Telescope* (June 2013): 16. When black holes and stars collide.

Jayawardhana, R. "Beyond Black." *Astronomy* (June 2002): 28. On finding evidence of the existence of event horizons and thus black holes.

Nadis, S. "Black Holes: Seeing the Unseeable." *Astronomy* (April 2007): 26. A brief history of the black hole idea and an introduction to potential new ways to observe them.

Psallis, D. & Sheperd, D. "The Black Hole Test." *Scientific American* (September 2015): 74–79. The Event Horizon Telescope (a network of radio telescopes) will test some of the stranger predictions of general relativity for the regions near black holes. The September 2015 issue of *Scientific American* was devoted to a celebration of the 100th anniversary of the general theory of relativity.

Rees, M. "To the Edge of Space and Time." *Astronomy* (July 1998): 48. Good, quick overview.

Talcott, R. "Black Holes in our Backyard." *Astronomy* (September 2012): 44. Discussion of different kinds of black holes in the Milky Way and the 19 objects known to be black holes.

##### **Gravitational Waves**

Bartusiak, M. "Catch a Gravity Wave." *Astronomy* (October 2000): 54.

Gibbs, W. "Ripples in Spacetime." *Scientific American* (April 2002): 62.

Haynes, K., & Betz, E. "A Wrinkle in Spacetime Confirms Einstein's Gravitation." *Astronomy* (May 2016): 22. On the direct detection of gravity waves.

Sanders, G., and Beckett, D. "LIGO: An Antenna Tuned to the Songs of Gravity." *Sky & Telescope* (October 2000): 41.

## Websites

### Black Holes

Black Hole Encyclopedia: <http://blackholes.stardate.org> (<http://blackholes.stardate.org>). From StarDate at the University of Texas McDonald Observatory.

Black Holes: <http://science.nasa.gov/astrophysics/focus-areas/black-holes> (<http://science.nasa.gov/astrophysics/focus-areas/black-holes>). NASA overview of black holes, along with links to the most recent news and discoveries.

Introduction to Black Holes: <https://www.newscientist.com/article/dn18348-introduction-black-holes/> (<https://www.newscientist.com/article/dn18348-introduction-black-holes/>). Basic information from New Scientist magazine.

Virtual Trips into Black Holes and Neutron Stars: [http://antwrp.gsfc.nasa.gov/htmltest/rjn\\_bht.html](http://antwrp.gsfc.nasa.gov/htmltest/rjn_bht.html) ([http://antwrp.gsfc.nasa.gov/htmltest/rjn\\_bht.html](http://antwrp.gsfc.nasa.gov/htmltest/rjn_bht.html)). By Robert Nemiroff at Michigan Technological University.

### Gravitational Waves

Advanced LIGO: <https://www.advancedligo.mit.edu> (<https://www.advancedligo.mit.edu>). The full story on this gravitational wave observatory.

eLISA: <https://www.elisascience.org> (<https://www.elisascience.org>).

Gravitational Waves Detected, Confirming Einstein's Theory: <http://www.nytimes.com/2016/02/12/science/ligo-gravitational-waves-black-holes-einstein.html> (<http://www.nytimes.com/2016/02/12/science/ligo-gravitational-waves-black-holes-einstein.html>). *New York Times* article and videos on the discovery of gravitational waves.

Gravitational Waves Discovered from Colliding Black Holes: <http://www.scientificamerican.com/article/gravitational-waves-discovered-from-colliding-black-holes1> (<http://www.scientificamerican.com/article/gravitational-waves-discovered-from-colliding-black-holes1>). *Scientific American* coverage of the discovery of gravitational waves (note the additional materials available in the menu at the right).

LIGO Caltech: <https://www.ligo.caltech.edu> (<https://www.ligo.caltech.edu>).

## Videos

### Black Holes

Black Holes: The End of Time or a New Beginning?: <https://www.youtube.com/watch?v=mgtJRsdKe6Q> (<https://www.youtube.com/watch?v=mgtJRsdKe6Q>). 2012 Silicon Valley Astronomy Lecture by Roger Blandford (1:29:52).

Death by Black Hole: <https://www.youtube.com/watch?v=h1ijXOUMJpg> (<https://www.youtube.com/watch?v=h1ijXOUMJpg>). Neil deGrasse Tyson explains spaghettification with only his hands (5:34).

Hearts of Darkness: Black Holes in Space: <https://www.youtube.com/watch?v=4tiAOldypLk> (<https://www.youtube.com/watch?v=4tiAOldypLk>). 2010 Silicon Valley Astronomy Lecture by Alex Filippenko (1:56:11).

### Gravitational Waves

Journey of a Gravitational Wave: <https://www.youtube.com/watch?v=FIDtXIBrAYE> (<https://www.youtube.com/watch?v=FIDtXIBrAYE>). Introduction from LIGO Caltech (2:55).

LIGO's First Detection of Gravitational Waves: [https://www.youtube.com/watch?v=gw-i\\_VKd6Wo](https://www.youtube.com/watch?v=gw-i_VKd6Wo) ([https://www.youtube.com/watch?v=gw-i\\_VKd6Wo](https://www.youtube.com/watch?v=gw-i_VKd6Wo)). Explanation and animations from PBS Digital Studio (9:31).

Two Black Holes Merge into One: [https://www.youtube.com/watch?v=I\\_88S8DWbcU](https://www.youtube.com/watch?v=I_88S8DWbcU) ([https://www.youtube.com/watch?v=I\\_88S8DWbcU](https://www.youtube.com/watch?v=I_88S8DWbcU)). Simulation from LIGO Caltech (0:35).

What the Discovery of Gravitational Waves Means: <https://www.youtube.com/watch?v=jMVAgCPYYHY> (<https://www.youtube.com/watch?v=jMVAgCPYYHY>). TED Talk by Allan Adams (10:58).

### Collaborative Group Activities

- A. A computer science major takes an astronomy course like the one you are taking and becomes fascinated with black holes. Later in life, he founds his own internet company and becomes very wealthy when it goes public. He sets up a foundation to support the search for black holes in our Galaxy. Your group is the allocation committee of this foundation. How would you distribute money each year to increase the chances that more black holes will be found?
- B. Suppose for a minute that stars evolve *without* losing any mass at any stage of their lives. Your group is given a list of binary star systems. Each binary contains one main-sequence star and one invisible companion. The spectral types of the main-sequence stars range from spectral type O to M. Your job is to determine whether any of the invisible companions might be black holes. Which ones are worth observing? Why? (Hint: Remember that in a binary star system, the two stars form at the same time, but the pace of their evolution depends on the mass of each star.)
- C. You live in the far future, and the members of your group have been convicted (falsely) of high treason. The method of execution is to send everyone into a black hole, but you get to pick which one. Since you are doomed to die, you would at least like to see what the inside of a black hole is like—even if you can't tell anyone outside about it. Would you choose a black hole with a mass equal to that of Jupiter or one with a mass equal to that of an entire galaxy? Why? What would happen to you as you approached the event horizon in each case? (Hint: Consider the difference in force on your feet and your head as you cross over the event horizon.)
- D. General relativity is one of the areas of modern astrophysics where we can clearly see the frontiers of human knowledge. We have begun to learn about black holes and warped spacetime recently and are humbled by how much we still don't know. Research in this field is supported mostly by grants from government agencies. Have your group discuss what reasons there are for our tax dollars to support such "far out" (seemingly impractical) work. Can you make a list of "far out" areas of research in past centuries that later led to practical applications? What if general relativity does not have many practical applications? Do you think a small part of society's funds should still go to exploring theories about the nature of space and time?
- E. Once you all have read this chapter, work with your group to come up with a plot for a science fiction story that uses the properties of black holes.
- F. Black holes seem to be fascinating not just to astronomers but to the public, and they have become part of popular culture. Searching online, have group members research examples of black holes in music, advertising, cartoons, and the movies, and then make a presentation to share the examples you found with the whole class.

- G. As mentioned in the [Gravity and Time Machines](#) feature box in this chapter, the film *Interstellar* has a lot of black hole science in its plot and scenery. That's because astrophysicist Kip Thorne at Caltech had a big hand in writing the initial treatment for the movie, and later producing it. Get your group members together (be sure you have popcorn) for a viewing of the movie and then try to use your knowledge of black holes from this chapter to explain the plot. (Note that the film also uses the concept of a *wormhole*, which we don't discuss in this chapter. A wormhole is a theoretically possible way to use a large, spinning black hole to find a way to travel from one place in the universe to another without having to go through regular spacetime to get there.)



## Exercises

### Review Questions

1. How does the equivalence principle lead us to suspect that spacetime might be curved?
2. If general relativity offers the best description of what happens in the presence of gravity, why do physicists still make use of Newton's equations in describing gravitational forces on Earth (when building a bridge, for example)?
3. Einstein's general theory of relativity made or allowed us to make predictions about the outcome of several experiments that had not yet been carried out at the time the theory was first published. Describe three experiments that verified the predictions of the theory after Einstein proposed it.
4. If a black hole itself emits no radiation, what evidence do astronomers and physicists today have that the theory of black holes is correct?
5. What characteristics must a binary star have to be a good candidate for a black hole? Why is each of these characteristics important?
6. A student becomes so excited by the whole idea of black holes that he decides to jump into one. It has a mass 10 times the mass of our Sun. What is the trip like for him? What is it like for the rest of the class, watching from afar?
7. What is an event horizon? Does our Sun have an event horizon around it?
8. What is a gravitational wave and why was it so hard to detect?
9. What are some strong sources of gravitational waves that astronomers hope to detect in the future?
10. Suppose the amount of mass in a black hole doubles. Does the event horizon change? If so, how does it change?

### Thought Questions

11. Imagine that you have built a large room around the people in [Figure 24.4](#) and that this room is falling at exactly the same rate as they are. Galileo showed that if there is no air friction, light and heavy objects that are dropping due to gravity will fall at the same rate. Suppose that this were not true and that instead heavy objects fall faster. Also suppose that the man in [Figure 24.4](#) is twice as massive as the woman. What would happen? Would this violate the equivalence principle?
12. A monkey hanging from a tree branch sees a hunter aiming a rifle directly at him. The monkey then sees a flash and knows that the rifle has been fired. Reacting quickly, the monkey lets go of the branch and drops so that the bullet can pass harmlessly over his head. Does this act save the monkey's life? Why or why not? (Hint: Consider the similarities between this situation and that of [Exercise 24.11](#).)
13. Why would we not expect to detect X-rays from a disk of matter about an ordinary star?

14. Look elsewhere in this book for necessary data, and indicate what the final stage of evolution—white dwarf, neutron star, or black hole—will be for each of these kinds of stars.
  - A. Spectral type-O main-sequence star
  - B. Spectral type-B main-sequence star
  - C. Spectral type-A main-sequence star
  - D. Spectral type-G main-sequence star
  - E. Spectral type-M main-sequence star
15. Which is likely to be more common in our Galaxy: white dwarfs or black holes? Why?
16. If the Sun could suddenly collapse to a black hole, how would the period of Earth's revolution about it differ from what it is now?
17. Suppose the people in [Figure 24.4](#) are in an elevator moving upward with an acceleration equal to  $g$ , but in the opposite direction. The woman throws the ball to the man with a horizontal force. What happens to the ball?
18. You arrange to meet a friend at 5:00 p.m. on Valentine's Day on the observation deck of the Empire State Building in New York City. You arrive right on time, but your friend is not there. She arrives 5 minutes late and says the reason is that time runs faster at the top of a tall building, so she is on time but you were early. Is your friend right? Does time run slower or faster at the top of a building, as compared with its base? Is this a reasonable excuse for your friend arriving 5 minutes late?
19. You are standing on a scale in an elevator when the cable snaps, sending the elevator car into free fall. Before the automatic brakes stop your fall, you glance at the scale reading. Does the scale show your real weight? An apparent weight? Something else?

### Figuring for Yourself

20. Look up  $G$ ,  $c$ , and the mass of the Sun in [Appendix E](#) and calculate the radius of a black hole that has the same mass as the Sun. (Note that this is only a theoretical calculation. The Sun does not have enough mass to become a black hole.)
21. Suppose you wanted to know the size of black holes with masses that are larger or smaller than the Sun. You could go through all the steps in [Exercise 24.20](#), wrestling with a lot of large numbers with large exponents. You could be clever, however, and evaluate all the constants in the equation once and then simply vary the mass. You could even express the mass in terms of the Sun's mass and make future calculations really easy. Show that the event horizon equation is equivalent to saying that the radius of the event horizon is equal to 3 km times the mass of the black hole in units of the Sun's mass.
22. Use the result from [Exercise 24.21](#) to calculate the radius of a black hole with a mass equal to: the Earth, a B0-type main-sequence star, a globular cluster, and the Milky Way Galaxy. Look elsewhere in this text and the appendixes for tables that provide data on the mass of these four objects.
23. Since the force of gravity a significant distance away from the event horizon of a black hole is the same as that of an ordinary object of the same mass, Kepler's third law is valid. Suppose that Earth collapsed to the size of a golf ball. What would be the period of revolution of the Moon, orbiting at its current distance of 400,000 km? Use Kepler's third law to calculate the period of revolution of a spacecraft orbiting at a distance of 6000 km.