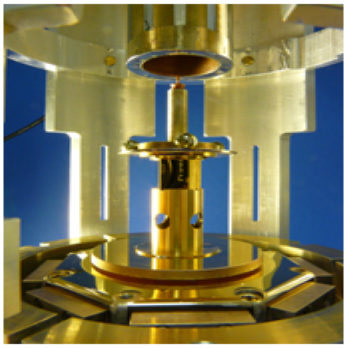
Unit 3: Gravity



© Ted Cook.

Unit Overview

Although by far the weakest of the known forces in nature, gravity pervades the universe and played an essential role in the evolution of the universe to its current state. Newton's law of universal gravitation and its elegant successor, Einstein's theory of general relativity, represent milestones in the history of science and provide the best descriptions we have of gravity. General relativity is founded on the principle of equivalence of gravity and acceleration; an inescapable consequence is that gravity governs the very geometry of space and time. This property of gravity distinguishes it from the other forces and makes attempts to unify all of the forces into a "theory of everything" exceedingly difficult. How well do we really understand gravity? Do the same laws of gravity apply to objects on the opposite sides of the universe as to particles in the microscopic quantum world? Current research is attempting to improve the precision to which the laws of gravity have been tested and to expand the realm over which tests of gravity have been made. Gravitational waves, predicted by general relativity, are expected to be observed in the near future. This unit will review what we know about gravity and describe many of the directions that research in gravitation is following.

Content for This Unit

Sections:

1. Introduction.. 2
2. Nature's Strongest and Weakest Force.. 4
3. Newton's Law of Universal Gravitation.. 8
4. Gravitational and Inertial Mass.. 12
5. Testing the Law of Universal Gravitation.. 15
6. The Theory of General Relativity.. 21
7. Gravitational Waves.. 27
8. Gravity and Quantum Mechanics.. 36
9. Further Reading.. 40

Glossary.. 41

Section 1: Introduction

Any two objects, regardless of their composition, size, or distance apart, feel a force that attracts them toward one another. We know this force as gravity. The study of gravity has played a central role in the history of science from the 17th century, during which Galileo Galilei compared objects falling under the influence of gravity and Sir Isaac Newton proposed the law of universal gravitation, to the 20th century and Albert Einstein's theory of general relativity, to the present day, when intense research in gravitational physics focuses on such topics as black holes, gravitational waves, and the composition and evolution of the universe.

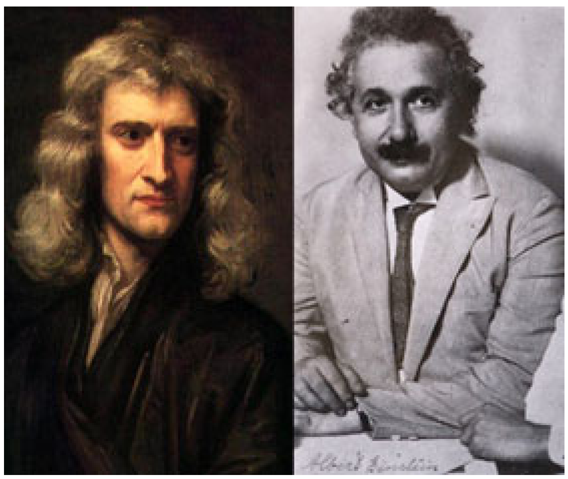


Figure 1: Portraits of Sir Isaac Newton (left) and Albert Einstein (right).
Source: © Image of Newton: Wikimedia Commons, Public Domain; Image of Einstein: Marcelo Gleiser.

Any study of gravity must accommodate two antithetical facts. In many ways, gravity is the dominant force in the universe. Yet, of the four forces known in nature, gravity is by far the weakest. The reason for that weakness remains a major unanswered question in science. Gravity also forms the central focus of efforts to create a "theory of everything" by unifying all four forces of nature. Ironically, gravity was responsible for the first unification of forces, when Newton identified the force that caused an apple to fall to Earth to be the same as the force that held the Moon in orbit.

Current research on gravity takes several forms. Experiments with ever-greater precision seek to test the foundations of gravitational theory such as the universality of free fall and the inverse square law. Other experimentalists are developing ways to detect the gravitational waves predicted by Einstein's general relativity theory and to understand the fundamental nature of gravity at the largest and smallest units of length. At the same time, theorists are exploring new approaches to gravity that extend Einstein's monumental work in the effort to reconcile quantum mechanics and general relativity.

Section 2: Nature's Strongest and Weakest Force

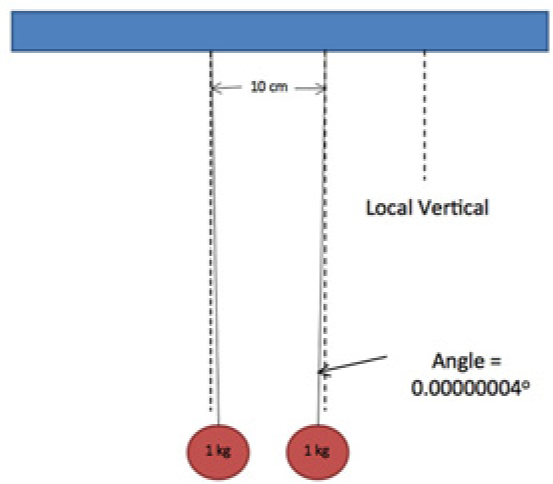


Figure 2: Gravitational attraction between two spheres causes a tiny change in their positions.
Source: © Blayne Heckel.

How weak is gravity? We can find out by comparing the gravitational force with the electromagnetic force, the other long-range force in nature, in the case of a hydrogen atom. By using Coulomb's law of electrical attraction and repulsion we can compute the magnitude of the attractive electrical force, F_E, between the electron and proton and Newton's Law of universal gravitation, which we will discuss in the next section, to calculate the magnitude of the gravitational force, F_G, between the two particles. We find that $F_G/F_E \approx 4 \times 10^{-40}$. Because both forces decrease as the square of the distance between the objects, the gravitational force between the electron and proton remains almost 39 orders of magnitude weaker than the electric force at all distances. That is a number so large that we can hardly fathom it: roughly the ratio of the size of the observable universe to the size of an atomic nucleus. Relatively speaking, at short distances the strong, weak, and electromagnetic forces all have comparable strengths, 39 orders of magnitude stronger than gravity.

The contrast has practical consequences. We can easily feel the magnetic force between two refrigerator magnets, yet we don't feel the gravitational force of attraction between our hands when they are near to one another. The force is there, but too weak to notice. Physicists use sensitive instruments such as the torsion balances that we discuss below to detect the gravitational force between small objects. But the measurements require great care to ensure that residual electric and magnetic forces do not overwhelm the feeble gravitational effects.

Nevertheless, gravity is the force we experience most often. Whether lifting our arms, climbing a staircase, or throwing a ball, we routinely feel and compensate for the effects of our gravitational attraction to the Earth in our daily lives. We call the direction opposite to Earth's gravity "up." Removing the effects of Earth's gravity in a free fall off a diving board or the weightlessness of space leaves us disoriented. Gravity holds the Moon in orbit about the Earth, the Earth in orbit about the Sun, and the Sun in orbit about the center of our Milky Way galaxy. Gravity holds groups of galaxies together in clusters and, we believe, governs the largest structures in the universe.

Gravity's role in forming stars and galaxies

Gravity also caused stars and galaxies to form in the first place. The standard model of cosmology has the universe beginning in a Big Bang roughly 14 billion years ago, followed by an expansion that continues today. At an early age, before stars existed, the universe could be described as a nearly homogeneous gas of matter and radiation. The matter consisted mostly of hydrogen atoms, helium atoms, neutrinos, and dark matter (an unknown form of matter that interacts via gravity but whose exact nature is currently a field of intense research, as we shall see in Unit 10). In regions of space where the density of matter slightly exceeded the average, the gravitational attraction between the constituents of the matter caused the gas to coalesce into large clouds. Friction inside the clouds due to collisions between the atoms and further gravitational attraction caused regions of the clouds to coalesce to densities so high as to ignite nuclear fusion, the energy source of stars.

Figure 3: Hubble Space Telescope image of a star-forming region in the Small Magellanic Cloud.
Source: © NASA/ESA and A.Nota (STScI/ESA).

A massive star that has burnt all of its nuclear fuel can collapse under the influence of gravity into a black hole, a region of space where gravity is so strong that not even light can escape the gravitational pull. Near to a black hole, therefore, nature's weakest interaction exerts the strongest force in the universe.

How do physicists reconcile the incredible weakness of gravity relative to the electromagnetic force with the observation that gravity dominates the interactions between the largest objects in the universe? How can it take the gravitational attraction billions of years, as calculations show, to cause two hydrogen atoms starting just 10 cm apart to collide when we know that the hydrogen gas of the early universe condensed into enormous clouds and stars on a much quicker time scale? Why does Earth's gravity feel so strong while the gravitational forces between objects on the Earth are so small as to be difficult to detect? The answer, common to all of these questions, arises from the relative masses of the objects in question. Gravity is weak between objects that have small masses, but it grows in strength as the objects grow in mass. This seemingly simple answer reflects a profound difference between gravity and the other forces in nature.

Attraction without repulsion

Gravity is an attractive force that acts between any objects at any distance regardless of their composition. The property of matter that gives rise to this attraction is essentially the mass of the object.

The gravitational force between each atom in the Earth and each atom in our bodies is incredibly small. However, every one of the roughly 10^{50} atoms in the Earth attracts each of the approximately 10^{27} atoms in our bodies, leading to the appreciable force that we experience. In contrast, the other forces in nature can be both attractive and repulsive. The electric force is attractive between unlike charges and equally repulsive between like charges. Because ordinary matter, such as the Earth or our bodies, consists of equal numbers of positive and negative charges bound closely together in atoms, the net electric force between electrically neutral objects essentially vanishes.

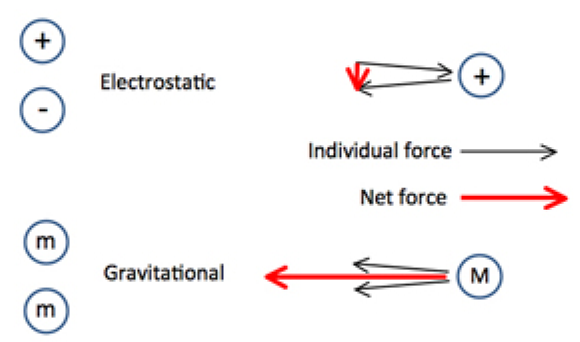


Figure 4: Electrostatic and gravitational shielding.
Source: © Blayne Heckel.

If we place an electric charge inside an otherwise empty grounded metal box, then a charge outside of the box is unaffected by the charge inside. This "electrical shielding" arises from the movement of charges within the metal that rearrange themselves to cancel the electric force of the charge inside. If instead, we place a mass inside a grounded metal box or any other kind of box, another mass placed outside of the box will always feel its gravitational pull, as well as the pull from the mass of the box itself. Because the gravitational force has only one sign—attractive—it cannot be shielded. Every particle, whether normal or dark matter, in regions of the early universe that had slightly higher than average density gravitationally attracted nearby particles more strongly than did regions with less than average density. Gravity caused the matter to coalesce into the structures in the universe that we see today.

As we stand at rest, the few square inches of our feet in contact with the ground oppose the downward gravitational pull of all 10^{50} atoms in the Earth. What counteracts gravity is the electrical repulsion between the outermost electrons of the soles of our shoes and the electrons at the ground's surface. The mere act of standing embodies the contrast between the weak but cumulative gravitational attraction and the much stronger but self-canceling electric force.

Section 3: Newton's Law of Universal Gravitation

An underlying theme in science is the idea of unification—the attempt to explain seemingly disparate phenomena under the umbrella of a common theoretical framework. The first major unification in physics was Sir Isaac Newton's realization that the same force that caused an apple to fall at the Earth's surface—gravity—was also responsible for holding the Moon in orbit about the Earth. This universal force would also act between the planets and the Sun, providing a common explanation for both terrestrial and astronomical phenomena.

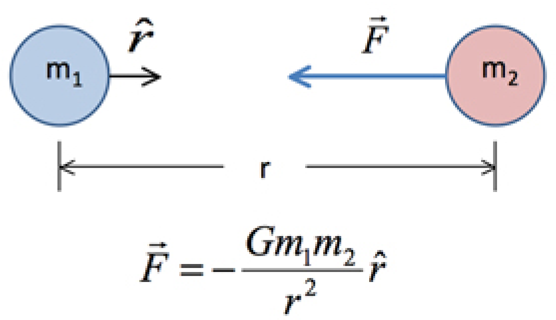


Figure 5: Newton's law of universal gravitation.
Source: © Blayne Heckel.

Newton's law of universal gravitation states that *every two particles attract one another with a force that is proportional to the product of their masses and inversely proportional to the square of the distance between them*. The proportionality constant, denoted by G, is called the universal gravitational constant. We can use it to calculate the minute size of the gravitational force inside a hydrogen atom. If we assign m_1 the mass of a proton, 1.67×10^{-27} kilograms and m_2 the mass of an electron, 9.11×10^{-31} kilograms, and use 5.3×10^{-11} meters as the average separation of the proton and electron in a hydrogen atom, we find the gravitational force to be 3.6×10^{-47} Newtons. This is approximately 39 orders of magnitude smaller than the electromagnetic force that binds the electron to the proton in the hydrogen nucleus. See the math

Local gravitational acceleration

The law of universal gravitation describes the force between point particles. Yet, it also accurately describes the gravitational force between the Earth and Moon if we consider both bodies to be points with all of their masses concentrated at their centers. The fact that the gravitational force from a spherically symmetric object acts as if all of its mass is concentrated at its center is a property of the inverse square dependence of the law of universal gravitation. If the force depended on distance in any other way, the resulting behavior would be much more complicated. A related property of an inverse square law force is that the net force on a particle inside of a spherically symmetric shell vanishes.

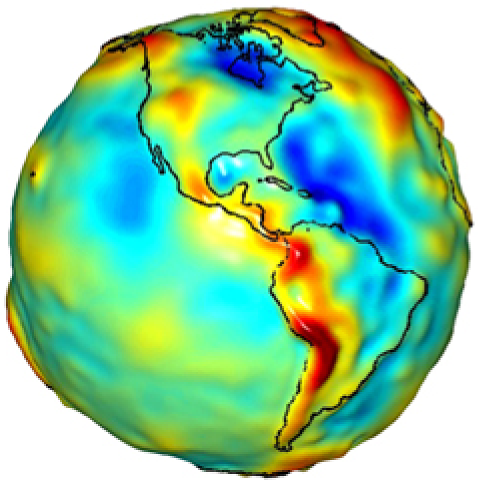


Figure 6: GRACE mission gravity map of the Earth.
Source: © Courtesy of The University of Texas Center for Space Research (NASA/DLR Gravity Recovery and Climate Experiment).

Just as we define an electric field as the electric force per unit charge, we define a gravitational field as the gravitational force per unit mass. The units of a gravitational field are the same units as acceleration, meters per second squared (m/s^2). For a point near the surface of the Earth, we can use Newton's law of universal gravitation to find the local gravitational acceleration, g. If we plug in the mass of the Earth for one of the two masses and the radius of the Earth for the separation between the two masses, we find that g is 9.81 m/s^2. This is the rate at which an object dropped near the Earth's surface will accelerate under the influence of gravity. Its velocity will increase by 9.8 meters per second, each second. Unlike big G, the universal gravitational constant, little g is not a constant. As we move up further from the Earth's surface, g decreases (by 3 parts in 10^5 for each 100 meters of elevation). But it also decreases as we descend down a borehole, because the mass that influences the local gravitational field is no longer that of the entire Earth but rather the total mass within the radius to which we have descended.

Even at constant elevation above sea level, g is not a constant. The Earth's rotation flattens the globe into an oblate spheroid; the radius at the equator is nearly 20 kilometers larger than at the poles, leading to a 0.5 percent larger value for g at the poles than at the equator. Irregular density distributions within the Earth also contribute to variations in g. Scientists can use maps of the gravitational field across the Earth's surface to infer what structures lay below the surface.

Gravitational fields and tides

Every object in the universe creates a gravitational field that pervades the universe. For example, the gravitational acceleration at the surface of the Moon is about one-sixth of that on Earth's surface. The gravitational field of the Sun at the position of the Earth is 5.9×10^{-3} m/s^2, while that of the Moon at the position of the Earth is 3.3×10^{-5} m/s^2, 180 times weaker than that of the Sun.

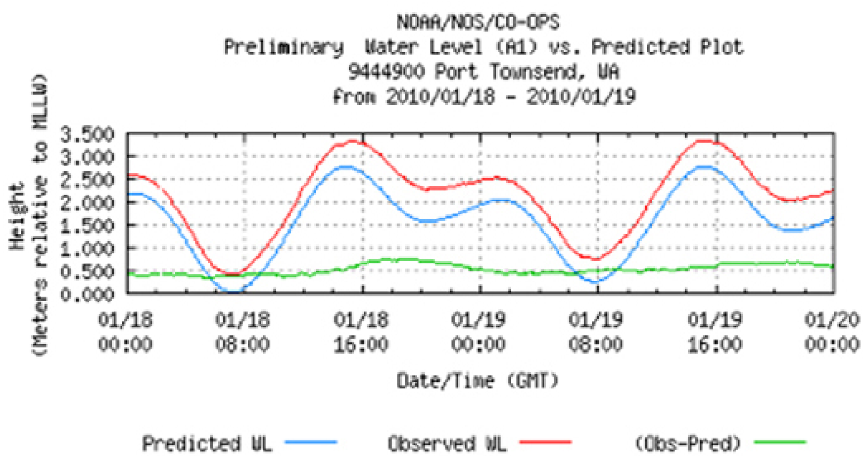


Figure 7: Plot of the tidal Water Level (WL) at Port Townsend, Washington.
Source: © NOAA.

The tides on Earth result from the gravitational pull of the Moon and Sun. Despite the Sun's far greater gravitational field, the lunar tide exceeds the solar tide. That's because it is not the gravitational field itself that produces the tides but its gradient—the amount the field changes from Earth's near side to its far side. If the Sun's gravitational field were uniform across the Earth, all points on and within the Earth would feel the same force, and there would be no relative motion (or tidal bulge) between them. However, because the gravitational field decreases as the inverse of the distance squared, the side of the Earth facing the Sun or Moon feels a larger field and the side opposite feels a smaller field than the field acting at Earth's center. The result is that water (and the Earth itself to a lesser extent) bulges toward the Moon or Sun on the near side and away on the far side, leading to tides twice a day. Because the Moon is much closer to Earth than the Sun, its gravitational gradient between the near and far sides of the Earth is more than twice as large as that of the Sun.

Section 4: Gravitational and Inertial Mass

A subtlety arises when we compare the law of universal gravitation with Newton's second law of motion. The mass that appears in the law of universal gravitation is the property of the particle that creates the gravitational force acting on the other particle; for if we double m_2, we double the force on m_1. Similarly, the mass in the law of universal gravitation is the property of the particle that responds to the gravitational force created by the other particle. The law of universal gravitation provides a definition of gravitational mass as the property of matter that creates and responds to gravitational forces. Newton's second law of motion, F=ma, describes how any force, gravitational or not, changes the motion of an object. For a given force, a large mass responds with a small acceleration and vice versa. The second law provides a definition of inertial mass as the property of matter that resists changes in motion or, equivalently, as an object's inertia.

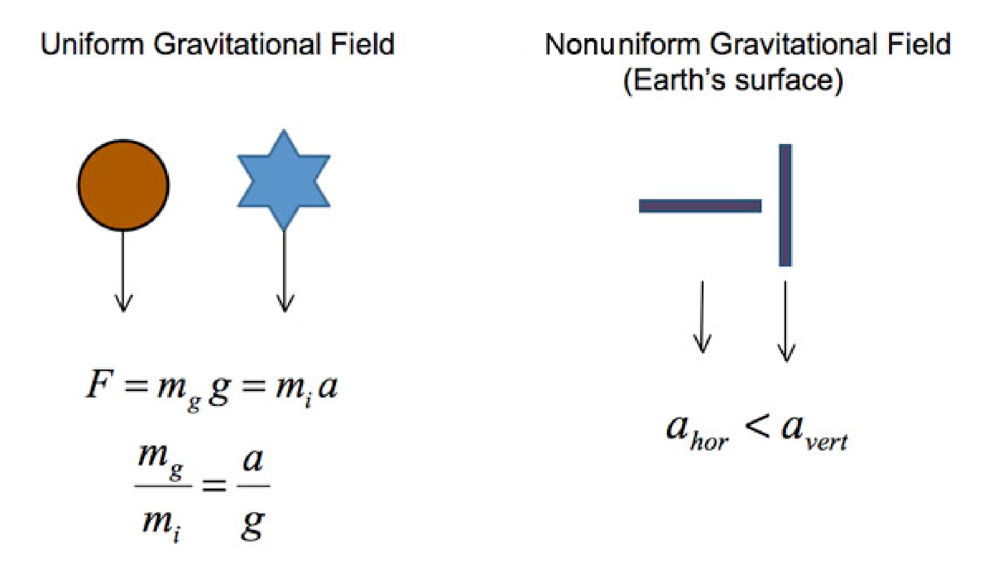


Figure 8: Equality of gravitational and inertial mass.
Source: © Blayne Heckel.

Is the inertial mass of an object necessarily the same as its gravitational mass? This question troubled Newton and many others since his time. Experiments are consistent with the premise that inertial and gravitational mass are the same. We can measure the weight of an object by suspending it from a spring balance. Earth's gravity pulls the object down with a force (weight) of $m_g g$, where g is the local gravitational acceleration and m_g the gravitational mass of the object. Gravity's pull on the object is balanced by the upward force provided by the stretched spring. We say that two masses that stretch identical springs by identical amounts have the same gravitational mass, even if they possess different sizes, shapes, or compositions. But will they have the same inertial mass? We can answer this question by cutting the springs, letting the masses fall, and measuring the accelerations. The second law says the net force acting on the mass is the product of the inertial mass, m_i, and acceleration, a, giving us: $m_g g = m_i a$ or $g/a = m_i/m_g$. But g is a property of the Earth alone and does not depend upon which object is placed at its surface, while experiments find the acceleration, a, to be the same for all objects falling from the same point in the absence of air friction. Therefore, g/a is the same for all objects and thus for m_i/m_g. We define the universal gravitational constant, G, to make $m_i = m_g$.

The principle of the universality of free fall is the statement that all materials fall at the same rate in a uniform gravitational field. This principle is equivalent to the statement that $m_i = m_g$. Physicists have found the principle to be valid within the limits of their experiments' precision, allowing them to use the same mass in both the law of universal gravitation and Newton's second law.

Measuring G

Measurements of planets' orbits about the Sun provide a value for the product GM_S, where M_S is the mass of the Sun. Similarly, earthbound satellites and the Moon's orbit provide a value for GM_E, where M_E is the mass of the Earth. To determine a value for G alone requires an *a priori* knowledge of both masses involved in the gravitational attraction. Physicists have made the most precise laboratory measurements of G using an instrument called a "torsion balance," or torsion pendulum. This consists of a mass distribution suspended by a long thin fiber. Unbalanced forces that act on the suspended mass distribution can rotate the mass distribution; the reflection of a light beam from a mirror attached to the pendulum measures the twist angle. Because a very weak force can twist a long thin fiber, even the tiny torques created by gravitational forces lead to measurable twist angles.

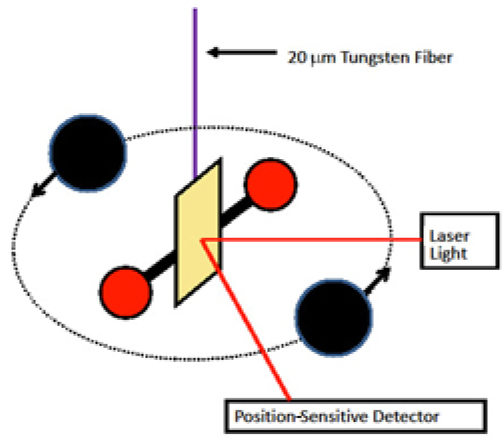


Figure 9: Schematic of a torsion balance to measure the gravitational constant, G.
Source: © Blayne Heckel.

To measure *G*, physicists use a dumbbell-shaped mass distribution (or more recently a rectangular plate) suspended by the fiber, all enclosed within a vacuum vessel. Precisely weighed and positioned massive spheres are placed on a turntable that surrounds the vacuum vessel. Rotating the turntable with the outer spheres about the fiber axis modulates the gravitational torque that the spheres exert on the pendulum and changes the fiber's twist angle.

This type of experiment accounts in large part for the currently accepted value of $(6.67428 \pm 0.00067) \times 10^{-11}$ N-m^2/kg^2 for the universal gravitational constant. It is the least precisely known of the fundamental constants because the weakness of gravity requires the use of relatively large masses, whose homogeneities and positioning are challenging to determine with high precision. Dividing GM_E found from satellite and lunar orbits by the laboratory value for G allows us to deduce the mass of the Earth: 5.98×10^{24} kilograms.

Section 5: Testing the Law of Universal Gravitation

Early successes of the law of universal gravitation included an explanation for Kepler's laws of planetary orbits and the discovery of the planet Neptune. Like any physical law, however, its validity rests on its agreement with experimental observations. Although the theory of general relativity has replaced the law of universal gravitation as our best theory of gravity, the three elements of the universal law —the universal constant of gravitation, the equality of gravitational and inertial mass, and the inverse square law—are also key elements of general relativity. To test our understanding of gravity, physicists continue to examine these elements of the universal law of gravitation with ever-increasing experimental sensitivity.

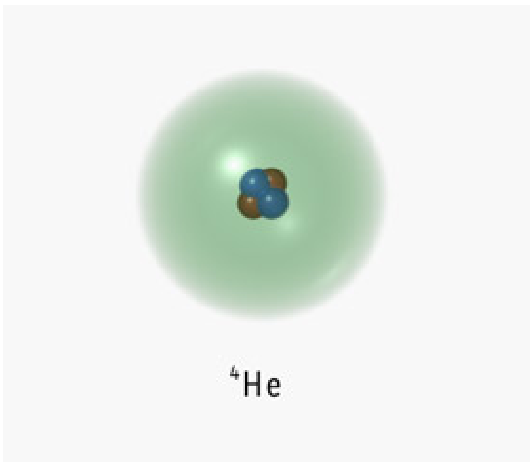


Figure 10: Mass of a helium atom is not equal to the sum of the individual masses of its constituent parts.
Source:

The mass of an object does not equal the sum of the masses of its constituents. For example, the mass of a helium atom is about one part per thousand less than the sum of the masses of the two neutrons, two protons, and two electrons that comprise it. The mass of the Earth is about five parts in 10^{10} smaller than the sum of the masses of the atoms that make up our planet. This difference arises from the nuclear and electrostatic binding—or potential—energy that holds the helium atom together and the gravitational binding (potential) energy that holds the earth together.

The inertial mass of an object therefore has contributions from the masses of the constituents and from all forms of binding energy that act within the object. If $m_i = m_g$, gravity must act equally on the constituent masses and the nuclear, electrostatic, and gravitational binding energies. Is this indeed the case? Does the Sun's gravity act on both the atoms in the Earth and the gravitational binding energy that holds the Earth together? These are questions that have to be answered by experimental measurements. Modern tests of the universality of free fall tell us that the answer to these questions is yes, at least to within the precision that the measurements have achieved to date.

Tests of the universality of free fall

To test the universality of free fall (UFF), experimentalists compare the accelerations of different materials under the influence of the gravitational force of a third body, called the "source." Many of the most sensitive tests have come from torsion balance measurements. A recent experiment used eight barrel-shaped test bodies attached to a central frame, with four made of beryllium (Be) on one side and four of titanium (Ti) on the other. The denser titanium bodies were hollowed out to make their masses equal to those of the beryllium bodies while preserving the same outer dimensions. All surfaces on the pendulum were coated by a thin layer of gold. The vacuum vessel that surrounded and supported the torsion fiber and pendulum rotated at a slow uniform rate about the tungsten fiber axis. Any differential acceleration of the two types of test bodies toward an external source would have led to a twist about the fiber that changed in sign as the apparatus rotated through 180°. Essential to the experiment was the removal of all extraneous (nongravitational) forces acting on the test bodies.

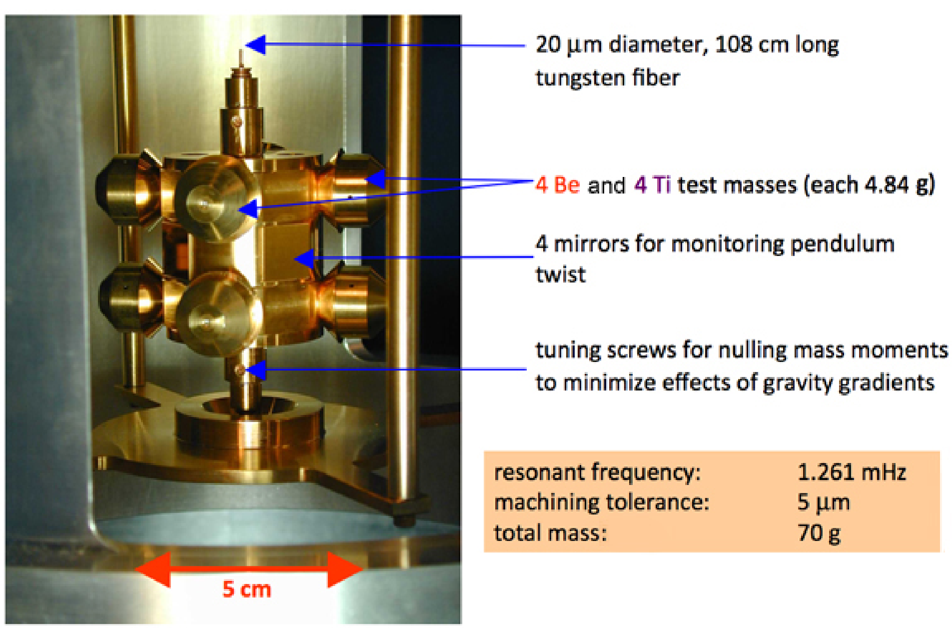


Figure 11: Torsion pendulum to test the universality of free fall.
Source: © Blayne Heckel.

For source masses, experiments have used locally constructed masses within the laboratory, local topographic features such as a hillside, the Earth itself, the Sun, and the entire Milky Way galaxy. Comparing the differential acceleration of test bodies toward the galactic center is of particular interest. Theorists think that dark matter causes roughly 30 percent of our solar system's acceleration about the center of the galaxy. The same dark matter force that helps to hold the solar system in orbit about the galactic center acts on the test bodies of a torsion pendulum. A dark matter force that acts differently on different materials would then lead to an apparent breakdown of the UFF. Because physicists have observed no differential acceleration in the direction of the galactic center, they conclude that dark matter interacts with ordinary matter primarily through gravity.

No violation of the UFF has yet been observed. Physicists use tests of the UFF to search for very weak new forces that may act between objects. Such forces would lead to an apparent violation of the UFF and would be associated with length scales over which the new forces act. Different experimental techniques have been used to test the UFF (and search for new forces) at different length scales. For example, there is a region between 10^3 meters and 10^5 meters over which torsion balances fail to produce reliable constraints on new weak forces. This is because over this length scale, we do not have sufficient knowledge of the density homogeneity of the Earth to calculate reliably the direction of the new force—it might point directly parallel to the fiber axis and not produce a torque on the pendulum. In this length range, the best limits on new forces come from modern "drop tower" experiments that directly compare the accelerations of different materials in free fall at the Earth's surface.

UFF tests in space

The future for tests of the UFF may lie in space-based measurements. In a drag-free satellite, concentric cylinders of different composition can be placed in free fall in the Earth's gravitational field. Experimentalists can monitor the relative displacement (and acceleration) of the two cylinders with exquisite accuracy for long periods of time using optical or superconducting sensors. Satellite-based measurements might achieve a factor of 1,000 times greater sensitivity to UFF violation than ground-based tests.

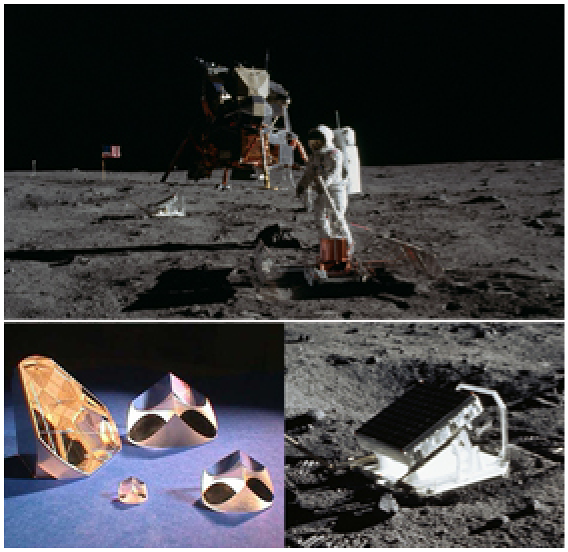


Figure 12: Apollo mission astronauts deploy corner cube reflectors.
Source: © NASA.

One source of space-based tests of the UFF already exists. The Apollo space missions left optical corner mirror reflectors on the Moon that can reflect Earth-based laser light. Accurate measurements of the time of flight of a laser pulse to the Moon and back provide a record of the Earth-Moon separation to a precision that now approaches 1 millimeter. Because both the Earth and the Moon are falling in the gravitational field of the Sun, this lunar laser ranging (LLR) experiment provides a test of the relative accelerations of the Earth and Moon toward the Sun with precision of 2×10^{-13} of their average accelerations. Gravitational binding energy provides a larger fraction of the Earth's mass than it does for the Moon. Were the UFF to be violated because gravity acts differently on gravitational binding energy than other types of mass or binding energy, then one would expect a result about 2,000 times larger than the experimental limit from LLR.

Validating the inverse square law

Physicists have good reason to question the validity of the inverse square law at both large and short distances. Short length scales are the domain of the quantum world, where particles become waves and we can no longer consider point particles at rest. Finding a theory that incorporates gravity within quantum mechanics has given theoretical physicists a daunting challenge for almost a century; it remains an open question. At astronomical length scales, discrepancies between observations and the expectations of ordinary gravity require dark matter and dark energy to be the dominant constituents of the universe. How sure are we that the inverse square law holds at such vast distances?

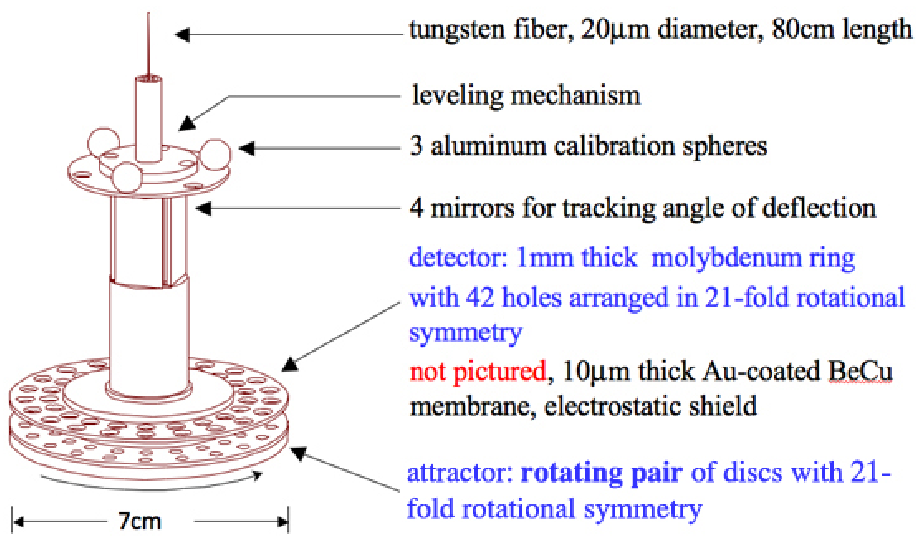


Figure 13: Torsion pendulum to test the inverse square law of gravity at submillimeter distances.
Source: © Blayne Heckel.

The inverse square law has been tested over length scales ranging from 5 x 10^{-5} to 10^{15} meters. For the large lengths, scientists monitor the orbits of the planets, Moon, and spacecraft with high accuracy and compare them with the orbits calculated for a gravitational force that obeys the inverse square law (including small effects introduced by the theory of general relativity). Adding an additional force can lead to measurable modifications of the orbits. For example, general relativity predicts that the line connecting the perihelia and aphelia of an elliptical gravitational orbit (the points of closest and furthest approach to the Sun for planetary orbits, respectively) should precess slowly. Any violation of the inverse square law would change the precession rate of the ellipse's semi-major axis. So far, no discrepancy has been found between the observed and calculated orbits, allowing scientists to place tight limits on deviations of the inverse square law over solar system length scales.

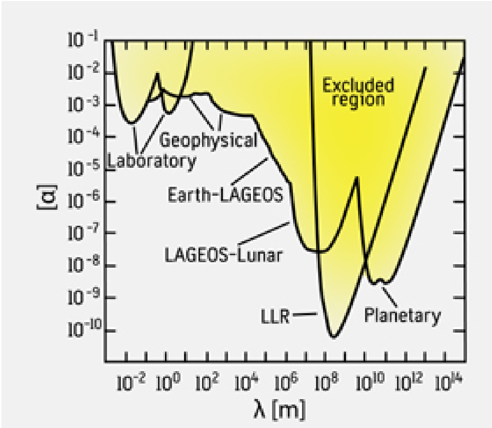


Figure 14: Experimental limits on the universality of free fall.
Source: © Blayne Heckel.

At the shortest distances, researchers measure the gravitational force between plates separated by about 5×10^{-5} meters, a distance smaller than the diameter of a human hair. A thin conducting foil stretched between the plates eliminates any stray electrical forces. Recent studies using a torsion pendulum have confirmed the inverse square law at submillimeter distances. To probe even shorter distances, scientists have etched miniature (micro) cantilevers and torsion oscillators from silicon wafers. These devices have measured forces between macroscopic objects as close as 10^{-8} meters, but not yet with enough sensitivity to isolate the gravitational force.

Does the inverse square law hold at the tiny distances of the quantum world and at the large distances where dark matter and dark energy dominate? We don't know the answer to that question. Definitive tests of gravity at very small and large length scales are difficult to perform. Scientists have made progress in recent years, but they still have much to learn.

Section 6: The Theory of General Relativity

The law of universal gravitation describes a force that acts instantaneously between objects separated by arbitrarily large distances. This behavior is in conflict with the theory of special relativity, which forbids the transfer of information faster than the speed of light. So how does one construct a theory of gravity that is consistent with special relativity?

Einstein found the key: the apparent equivalence between gravity and acceleration. Imagine that you are in a windowless rocket ship far from any stars or planets. With the rocket engines turned off, you and everything else not secured to the rocket float freely in weightlessness within the rocket's cabin. When turned on, the rocket engines provide a constant acceleration—9.8 m/s^2, say—and you stand firmly on the floor directly above the engines. In fact, the floor pushes against your feet with the same force that the ground pushes against your feet when you stand on Earth. Einstein posed the question: Is there any experiment you could perform within your sealed rocket ship that could distinguish between being in a rocket with a constant acceleration of 9.8 m/s^2, or a rocket at rest on the launch pad on Earth?

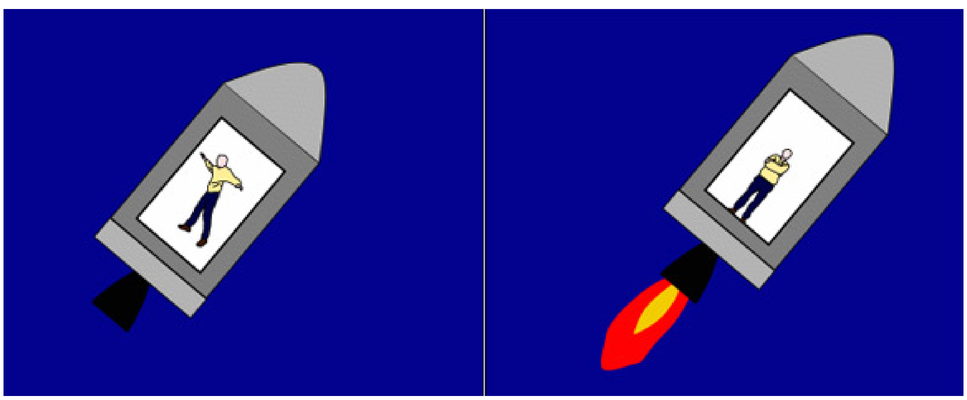


Figure 15: A person in an accelerating rocket feels the same downward pull as a person on Earth feels from gravity.
Source: © M. Poessel/Einstein Online/Max Planck Institute for Gravitational Physics.

Einstein concluded that the answer was no: There is no way to tell the difference between the presence of a uniform gravitational field and a frame of reference that has a constant acceleration. This observation embodies Einstein's principle of equivalence, the equivalence of gravity and acceleration, on which he built the theory of general relativity.

Gravitational lensing and the bending of light

We can use the equivalence between an accelerated reference frame and a frame with a uniform gravitational field to infer the behavior of light in a gravitational field. Imagine a beam of light traveling horizontally from one side of the rocket cabin to the other. With the rocket engines off, the light follows a straight path across the cabin in accordance with the laws of special relativity. With the engines on, causing constant acceleration, the cabin moves slightly upward in the time it takes the light to travel across the cabin. Hence, the light beam strikes a point lower on the cabin wall than when the engines were off. In the frame of the accelerating rocket, the light beam follows a curved (parabolic) path. Because an accelerating rocket is equivalent to a rocket at rest in a uniform gravitational field, a light beam will follow a curved path in a gravitational field; in other words, light is bent by gravity. A famous observation during a solar eclipse in 1919 confirmed that prediction: Measurements showed that starlight passing near the edge of the eclipsed Sun was deflected by an amount consistent with the principle of equivalence.

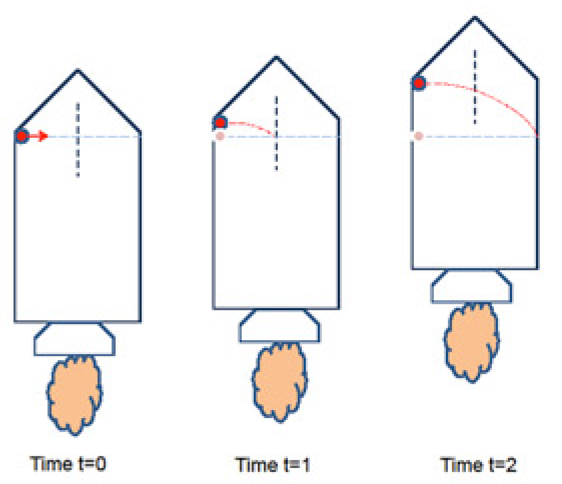


Figure 16: Bending of light in an accelerating rocket.
Source: © Blayne Heckel.

In the absence of gravity, a distant galaxy will appear to an observer on Earth to be a tiny source of light. However, if there are mass distributions such as other galaxies or clouds of dark matter near to the line sight between the Earth and the distant light source, the gravity from these mass distributions will bend the light from the distant galaxy. The image of the distant galaxy on Earth can then become a ring, one or multiple arcs, or even appear as several galaxies depending upon the location and distribution of the intervening mass. This distortion of light from distant sources is called gravitational lensing and is well established in observations from modern telescopes. The observed gravitational lensing is used to infer what sources of gravity lie between the Earth and distant light sources. A related phenomenon is an increase in intensity of the light observed from a distant source due to the passage of a massive object near to the line of sight. The gravitational field of the moving object acts as a lens, focusing more light into the telescope during the time that the massive object is near to the line of sight.

Gravitational time dilation

Returning to our rocket ship thought-experiment, imagine that a light beam travels from the ceiling to the floor of the accelerating rocket. In the time the beam takes to traverse the cabin, the cabin floor has acquired a larger velocity than it had when the light left the ceiling. A device on the floor measuring the frequency of the light would find a higher frequency than that of the emitted beam because of the Doppler shift, a phenomenon noticed most commonly in an ambulance siren that has a higher pitch as the ambulance approaches and a lower pitch as it recedes. The principle of equivalence then asserts that, in a gravitational field, a light beam traveling opposite to the field acquires a higher frequency, shifted toward the blue end of the spectrum; while a light beam shining upward from the Earth's surface decreases in frequency as it rises, the effect that we know as the gravitational redshift. Again, experiments have confirmed this phenomenon.

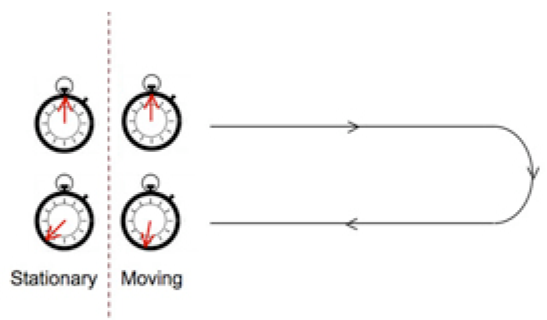


Figure 17: Time dilation and the twin paradox.
Source: © Blayne Heckel.

An inertial (nonaccelerating) observer sees no change in the light's frequency—the frequency associated with the atomic transition generating the light—as the light moves across the cabin, because it is traveling freely through empty space. Yet, an observer on the rocket floor, accelerating with the rocket, can use the same, now accelerating, atoms and atomic transitions as a clock (see Unit 5 for details); the observer defines a second as the time required for the fixed number of oscillations of a specific atomic transition. We concluded in the last paragraph that this accelerating observer will see the frequency of the light beam to be higher than the frequency of the same atomic transition in the measuring device. The inescapable conclusion is that the atomic clock (like all clocks) ticks more slowly in the accelerating frame of reference.

By the principle of equivalence, clocks in a gravitational field tick more slowly than in the absence of the field; the stronger the field, the more slowly the clock ticks. An atomic clock at sea level loses five microseconds per year relative to an identical clock at an altitude of 5,000 feet. We age more slowly at sea level than on a mountaintop. The global positioning system (GPS) relies heavily on the accuracy of clocks and corrects for the gravitational time dilation to achieve its fantastic precision.

Curved spacetime

The second key ingredient of general relativity is the notion of curved spacetime. Special relativity combines space and time into a four-dimensional spacetime, often referred to as "flat spacetime" or "Minkowski space." In flat spacetime, Euclidean geometry describes the spatial dimensions: Parallel lines never intersect, and the sum of the interior angles of a triangle is always 180 degrees. The two-dimensional analogue of flat space is the Cartesian plane, familiar from high school geometry class.

The surface of a sphere is also a two dimensional surface, but one that must be described by non-Euclidean geometry. Lines of constant longitude are parallel at the equator yet intersect at the poles. If you start at the equator and walk due north to the pole, turn right by 90 degrees, walk south to the equator, and then turn right again and walk along the equator, you will return to your original position having taken a triangular path on the Earth's surface. The sum of the interior angles of your triangular path is 270 degrees. A spherical surface is said to have positive curvature; a saddle-shaped surface has a negative curvature; and the sum of the interior angles of a triangle drawn on a saddle is less than 180 degrees.

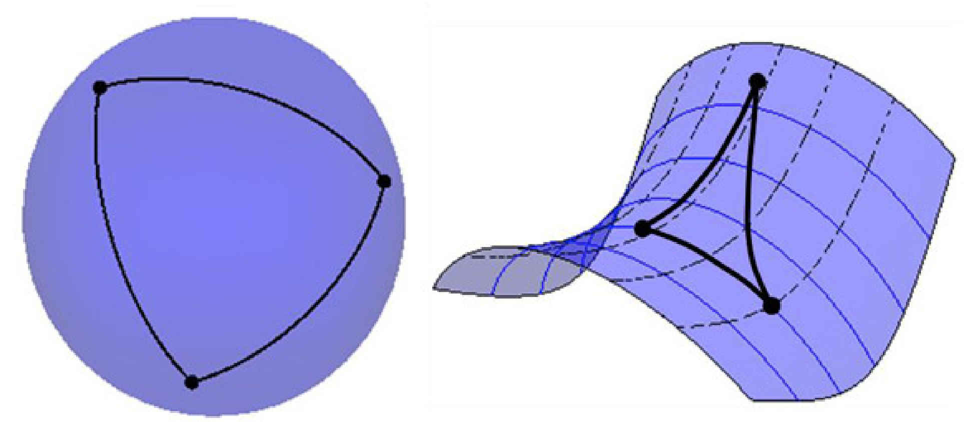


Figure 18: Triangles on curved surfaces.
Source: © Blayne Heckel.

Viewed from three dimensions, the shortest path between two points on a spherical or saddle-shaped surface is a curved line. This "geodesic" is the path that light would follow in that space. Three-dimensional space and four-dimensional spacetime, described by Riemannian geometry, can also be curved. The geodesics in spacetime are the paths that light beams follow—or, equivalently, the paths that observers in free fall follow. The Earth is in free fall about the Sun. We can construct a curved spacetime in which a circular orbit about the Sun is a geodesic. In such a spacetime, the Earth's orbit would stem from the curvature of spacetime rather than from a force acting between the Earth and the Sun.

The theory of general relativity takes the equivalence between motion in a gravitational field and motion in curved spacetime one step further. It asserts that what we call gravity is the bending of spacetime by matter. Rather than viewing gravity as a force acting between objects in flat spacetime, we should understand gravity as the interaction between matter and spacetime. The field equations of general relativity specify how matter and energy determine the curvature of spacetime. In turn, the spacetime curvature determines how the matter and energy will evolve.

Black holes

If enough matter and energy are concentrated in a small enough volume, general relativity predicts that spacetime can become so highly curved that a black hole is formed. A black hole is characterized by an event horizon, a surface surrounding the enclosed matter, through which nothing can escape; the event horizon represents a surface of no return. To an outside observer, the black hole is completely described by just three numbers: its mass, its electric charge, and its angular momentum.

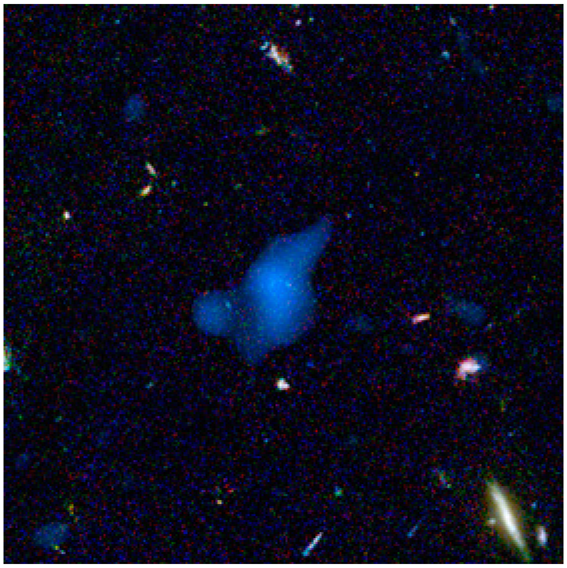


Figure 19: As gas falls into this supermassive black hole, it emits x-rays.
Source: © NASA, ESA, A.M. Koekemoer (STScI), M. Dickinson (NOAO), and the GOODS team.

Black holes can be created when a star of sufficient mass, after having burnt its nuclear fuel, collapses under its own weight. The black hole grows by capturing nearby matter and radiation that is pulled through the event horizon and by merging with astronomical objects such as stars, neutron stars, and other black holes. Massive black holes, millions to billions times more massive than our Sun, have been found near the center of many galaxies, including our own Milky Way. The black holes become visible when they accrete gas from the surrounding regions; the gas is accelerated and heated, producing observable radiation, before falling through the event horizon. The presence of a black hole can also be inferred from its gravitational influence on the orbits of nearby stars.

Section 7: Gravitational Waves

Gravitational waves are the gravitational analogues to electromagnetic waves—electric and magnetic fields that oscillate in the plane perpendicular to the direction that the wave travels. Similarly, gravitational waves are gravitational fields that oscillate perpendicular to the direction of travel. Unlike electromagnetic waves, which can be produced by a single oscillating electric charge, conservation of linear momentum requires at least two masses moving in opposition to produce gravitational waves. In the theory of special relativity, the constant c, called the speed of light, connects space with time and is the speed at which all massless particles travel. Like electromagnetic waves, gravitational waves are believed to propagate at the speed c.

General relativity predicts the existence of gravitational waves. In matter-free regions of spacetime where gravity is weak, the field equations of general relativity simplify to wave equations for spacetime itself. The solutions to these equations are transverse ripples in spacetime, propagating at the speed of light, which we identify as gravitational waves. The distortion of spacetime caused by a gravitational wave is distinctive: In the plane perpendicular to the direction the wave is travelling, space is stretched along one axis and compressed along the orthogonal axis, and vice versa one half-wave cycle later.

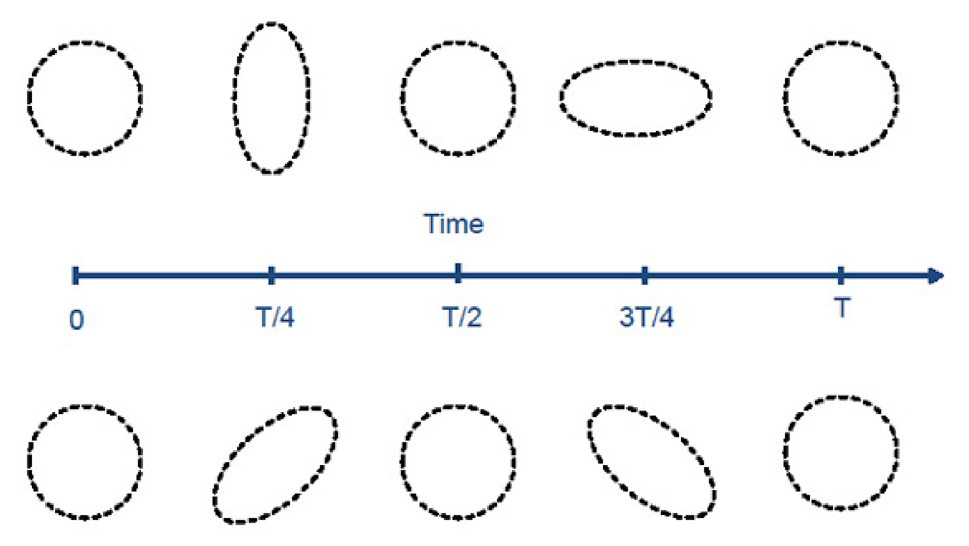


Figure 20: Distortion of space from a gravitational wave.
Source: © Blayne Heckel.

What are the similarities and differences between electromagnetic and gravitational waves? Both waves travel at speed c and carry with them energy and momentum. For electromagnetic waves, spacetime is the background medium in which the waves travel, while for gravitational waves, spacetime itself constitutes the waves. Electromagnetic waves are produced by accelerating or oscillating electric charges, while gravitational waves are produced by accelerating or oscillating mass distributions.

The frequencies of both waves reflect the oscillation frequencies of the sources that produce them. Electronic, vibrational, and rotational transitions (that is, oscillations) in atoms and molecules provide the most common source of electromagnetic waves, producing wave frequencies between roughly 10^7 and 10^{17} Hertz (Hz, or cycles per second). The most efficient sources for gravitational waves are massive objects undergoing rapid acceleration, such as pairs of neutron stars and/or black holes orbiting closely about one another. Considerations of orbital speeds and masses lead us to expect that the strongest gravitational radiation will have frequencies less than 10,000 Hz. Electromagnetic waves interact strongly with matter through absorption or scattering. Gravitational waves, by contrast, interact extremely weakly with matter; they travel essentially unimpeded through spacetime.

Indirect detection of gravitational waves

The most obvious difference between gravitational and electromagnetic waves is the fact that no one has yet directly detected gravitational waves—although this situation should change soon, given the significant progress in the technologies necessary for detection. In the meantime, we have strong indirect evidence that gravitational radiation exists. Astronomers have monitored the orbital frequency of the binary neutron star system PSR1913+16 since 1974, the year that Russell Hulse and Joseph Taylor discovered the system. One of the neutron stars is a pulsar that beams radio waves to the Earth as the neutron star rotates about its axis. Astrophysicists use the arrival times of the radio pulses to reconstruct the orbit of the binary system. The oscillating mass distribution of this binary system should generate gravitational waves and lose orbital energy as the waves radiate outward. A loss in orbital energy moves the neutron stars closer together and decreases the orbital period. The observed decrease of the orbital period over the past 35 years agrees with the energy loss through gravitational radiation predicted by general relativity to better than 1 percent accuracy.

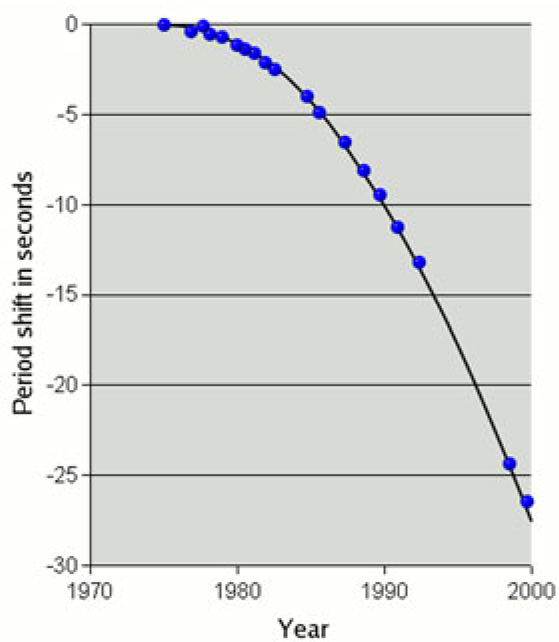


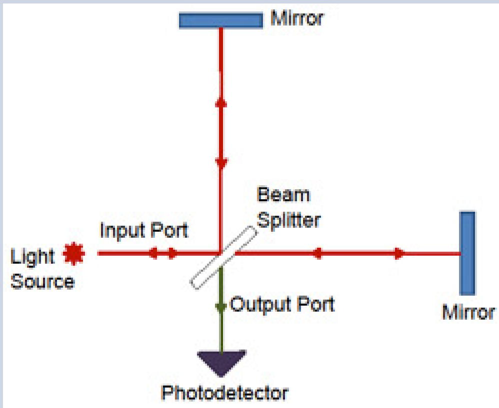
Figure 21: Orbital period of the binary neutron star system PSR 1913+15 measured from 1975 to 2000.
Source: © Wikimedia Commons, Public Domain. Author: M. Haynes et Lorimer, 2001.

Radio pulses from pulsars arrive at such a regular rate as to provide hope that pulsars may provide a means to detect very low frequency gravitational waves. Waves with frequencies around 10^{-9} Hz (equivalent to wavelengths of around 10 light-years) may persist from mass motions early in the history of the universe. When such a wave passes a pulsar, it slightly alters the arrival time of the radio beam from the pulsar. By comparing the arrival times of signals from perhaps 100 pulsars spread across the sky for many years, astronomers might possibly detect the tell-tale distortion of spacetime that is the signature of a passing gravitational wave.

Researchers believe that even lower frequency (that is, longer wavelength) gravitational waves were created in the early moments of the universe. We have evidence for events around 380,000 years after the Big Bang in the form of extraordinarily precise measurements of the cosmic microwave background (CMB), which is electromagnetic radiation left over from the early universe. Primordial gravitational waves would leave their imprint on the CMB as a distinctive polarization pattern as one compares the polarization of CMB radiation from different regions across the sky. Intense efforts are under way to mount instruments with enough polarization sensitivity to search for the primordial gravitational waves. Both ground-based observations (CLOVER, EBEX, Polarbear, QUIET, SPIDER, and SPUD instruments, to name a few) and space-based measurements from the Planck satellite launched in 2009 promise rapid progress toward the detection of primordial gravitational waves.

Direct detection of gravitational waves

The Classic Michelson Interferometer



Source: © Blayne Heckel.

Originally devised as part of the fruitless 19th century effort to identify the "ether" that supposedly suffused space, the Michelson interferometer now finds application in a 21st century experiment: the search for gravitational waves. The diagram shows the original version of the instrument.

A beam splitter divides laser light entering the input port into a transmitted beam and a reflected beam, perpendicular to each other. At the end of each beam's path, a mirror reflects the light back toward the beam splitter. If the two beams' paths have exactly the same length, the beams' electric fields oscillate in phase when the light returns to the beam splitter. The beams recombine to produce a beam that exits the beam splitter along the output port.

If the two paths differ in length by half a wavelength, they are out of phase. In that case, they interfere destructively at the beam splitter and no light exits from the output port. The intensity of light leaving the output port changes from a maximum to zero as the relative distance to the end mirrors changes by a quarter of a wavelength—about 2.5×10^{-7} meters for typical laser light. Precisely measuring this light intensity allows experimenters to detect even smaller relative displacements of the mirrors.

Any passing gravitational wave should compress spacetime in one direction and stretch it out in the perpendicular direction. Physicists believe that a modern version of the Michelson interferometer has the precise measuring ability that can detect the difference between the two.

The earliest attempts to detect gravitational waves directly used resonant mass detectors, also called "bar detectors," first developed by Joseph Weber. A typical bar detector might be a 5000 kg cylinder, two meters long, suspended in vacuum, and made from a low mechanical loss material such as certain alloys of aluminum. A burst of gravitational radiation could stretch and compress the bar, exciting the roughly one kilohertz lowest frequency vibrational mode of the cylinder. Sensors at the ends of the cylinder would detect the vibrations. A low-loss material would ring for many vibrational cycles, enhancing the ability to identify the excess vibration from a gravitational wave in the presence of background noise. Modern versions of the bar detectors (for example, the NAUTILUS and AURIGA detectors in Italy, miniGRAIL in the Netherlands, and the EXPLORER bar in Switzerland) are cooled to liquid helium temperatures or even lower to reduce the mechanical losses and thermal vibrations, and to reduce the noise inherent in the motion sensors.

Figure 22: Nautilus cryogenic antenna at the Laboratori Nazionali di Frascati, Italy.
Source: © Italian National Institute of Nuclear Physics (INFN)—National Laboratory of Frascati.

The most developed technology for the detection of gravitational waves involves long baseline laser interferometers. These instruments use laser light as a "meter stick" to compare the distances between a central object and distant objects along perpendicular axes. A passing gravitational wave will compress spacetime along one axis while stretching it along a perpendicular axis. An interferometer provides a precise measurement of the relative distance that light travels along different paths.

The long baseline gravitational wave interferometers are refined versions of the Michelson interferometer that, when it failed to detect the ether late in the 19th century, helped to set the scene for the theory of special relativity. But instead of being mounted rigidly on a table, the end mirrors of the gravitational wave instruments are suspended, like pendulums, from thin wires. In addition, the entire laser path occurs within a vacuum chamber. In the horizontal plane, the end mirrors are essentially objects in freefall, able to follow the stretching and compressing of spacetime from a gravitational wave. (In the classical picture of gravitational waves, the waves produce horizontal forces on the end mirrors; suspended mirrors can move in response to the wave forces.) However, even the strongest gravitational waves that one might hope to detect on Earth stretch space by an extremely small amount: The strain (change in distance divided by the distance) between two objects is expected to be less than 10^{-18}. To make the change in distance large enough for an interferometer to detect, designers must make the baseline as long as possible.

Gravitational wave discovery on Earth and in space

Figure 23: Aerial view of the LIGO Observatory at Hanford, Washington.
Source: © LIGO Laboratory.

The LIGO (Laser Interferometer Gravitational Wave Observatory) interferometers in the states of Louisiana and Washington each have end mirrors 4 kilometers from the beam splitter. VIRGO in Italy, GEO in Germany, and TAMA in Japan have separation distances of 3 kilometers, 600 meters, and 300 meters, respectively. With the 4-kilometer separation, physicists expect a strong gravitational wave to produce a relative change in distance between the mirrors and beam splitter of only about 4×10^{-15} meters, roughly the size of an atomic nucleus. Having several gravitational wave interferometers operating simultaneously greatly improves the chances of distinguishing a gravitational wave from the inevitable background sources of noise.

Ground-based gravitational wave interferometers are designed to detect waves with frequencies between roughly 10 Hz and 1,000 Hz. Sources for gravitational waves in this frequency band include the final moments of the in-spiral of orbiting pairs of neutron stars or black holes that lead to their collision and merger into a single object, violent astronomical events such as supernovae, and constant frequency signals such as those from a rapidly rotating neutron star that has a residual mass quadrupole moment.

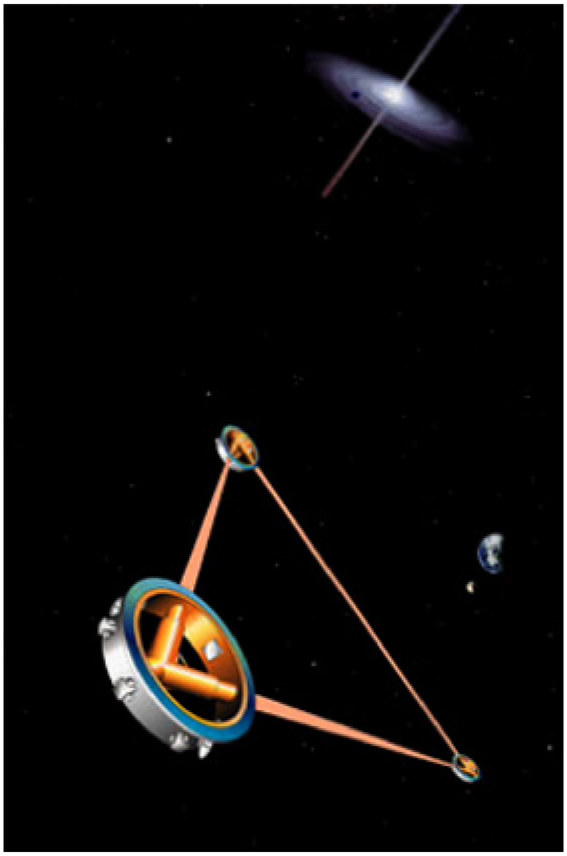


Figure 24: Artist's conception of the LISA satellites in space.
Source: © JPL/NASA.

Ground motion and seismic noise increase rapidly below a frequency of about 10 Hz and prevent Earth-based interferometers from detecting gravitational waves below this frequency limit. However, placing the interferometer on satellites in space allows us to avoid seismic noise and to envision much larger separations between the components of the interferometer. LISA (Laser Interferometer Space Antenna) is a joint NASA/European Space Agency proposal to launch three satellites into orbits to form an equilateral triangle with a distance of 5×10^6 kilometers between each spacecraft. Laser light exchanged between the spacecraft will measure the relative distances between them and may detect gravitational waves within a frequency range of 10^{-4} Hz to 0.1 Hz. Sources for gravitational waves in this frequency band include massive black hole binaries that form after galactic mergers, the orbits of stars as they spiral into black holes, and the gravitational radiation from the orbits of millions of compact binary systems within our

Milky Way galaxy. Once the detection of gravitational waves becomes routine, a new field of gravitational wave astronomy will be born.

Section 8: Gravity and Quantum Mechanics

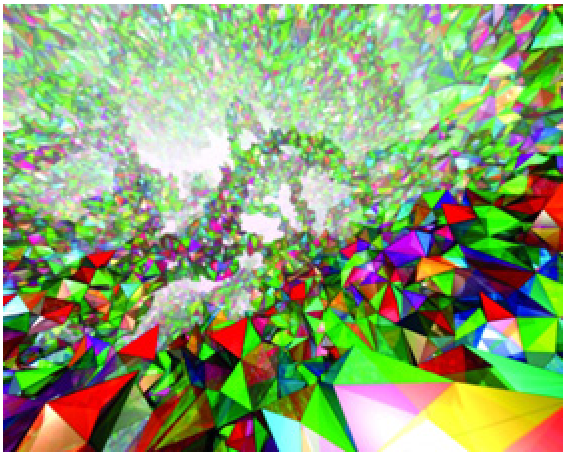


Figure 25: Visualization of a stage in the quantum evolution of geometry, according to Loop Quantum Gravity.
Source: © T. Thiemann (Max Planck Institute for Gravitational Physics (Albert Einstein Institute)) & Mildemarketing Science Communication.

Despite the fact that there is no experimental evidence that conflicts with the predictions of general relativity, physicists have found compelling reasons to suspect that general relativity may be only a good approximation to a more fundamental theory of gravity. The central issue is reconciling general relativity with the demands of quantum mechanics. Well tested by experiment, quantum mechanics is the theory that describes the microscopic behavior of particles. Unit 5 of this course will delve into the details of quantum mechanics. In the quantum world, particles are also waves, the results of measurements are probabilistic in nature, and an uncertainty principle forbids knowing certain pairs of measurable quantities, such as position and momentum, to arbitrary precision. The Standard Model described in the previous two units provides a unified picture of the strong, weak, and electromagnetic forces within the framework of quantum mechanics. Nonetheless, theoretical physicists have found it to be extremely difficult to construct a theory of quantum gravity that incorporates both general relativity and quantum mechanics.

At the atomic scale, gravity is some 40 orders of magnitude weaker than the other forces in nature. In both general relativity and Newtonian gravity, the strength of gravity grows at shorter and shorter distances, while quantum effects prevent the other forces from similarly increasing in strength. At a distance of approximately 10^{-35} m, called the Planck length, gravity becomes as strong as the other forces. At the Planck length, gravity is so strong and spacetime is so highly distorted that our common notions of space and time lose meaning. Quantum fluctuations at this length scale produce energies so large that microscopic black holes would pop into and out of existence. A theory of quantum gravity is needed to provide a description of nature at the Planck length. Yet, attempts by researchers to construct such a theory, analogous to the Standard Model of particle physics, have lead to serious inconsistencies.

Theories of quantum gravity

A significant difference between a quantum theory of gravity and the Standard Model of particle physics is the role of spacetime in the theory. In the Standard Model, spacetime is a background in which the quantum particles interact. In quantum gravity, spacetime itself participates in the interactions and acquires quantum fluctuations. Theorists have proposed radically new ideas about spacetime at microscopic distances to serve as foundations for theories of quantum gravity. Loop Quantum Gravity is an approach in which spacetime itself arises from the theory as a grid of discrete (quantized) loops of gravitational field lines called "spin networks." In Causal Dynamical Triangulation, spacetime is two-dimensional at the Planck length scale and evolves into our four-dimensional spacetime at larger length scales.

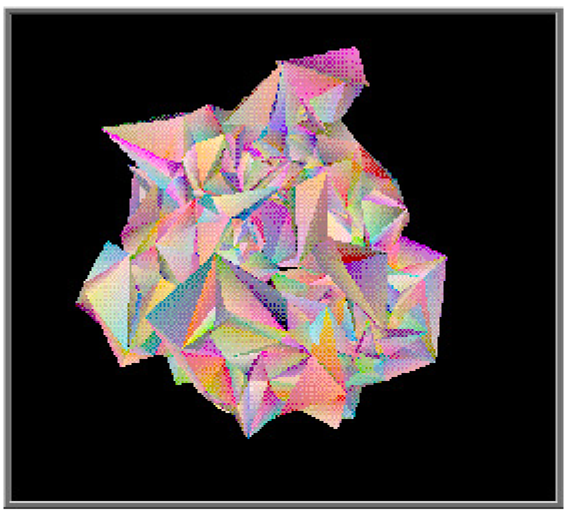


Figure 26: Causal Dynamical Triangulation builds the spacetime in which we live from tiny triangles.
Source: © Paul Coddington, University of Adelaide.

The most studied candidate for a theory of quantum gravity, string theory, posits that elementary particles are not points in spacetime but rather one-dimensional objects like open lengths or closed loops of string. Different modes of vibrations of the elementary strings give rise to the spectrum of particles in nature including the graviton, the particle that carries the gravitational force (analogous to the photon in electromagnetism). To provide a realistic theory of quantum gravity, string theories require extra spatial dimensions, each normally viewed as being finite in extent, such as a one-dimensional circle with a radius of the Planck length or larger. The presence of extra dimensions and new particles associated with gravity in string theories alters the gravitational inverse square law and the equivalence principle at very short distances. We will learn more about string theory and extra dimensions in Unit 4.

The small length scales and equivalently high energy scales at which quantum effects should modify gravity are far beyond the reach of current experimental techniques. A major challenge to finding the correct theory of quantum gravity is that it will be difficult to find experimental evidence to point us in the right direction.

Gravity at large distances

We can also wonder how well we know the behavior of gravity at very large lengths scales. As we have seen, the inverse square law of gravity has been verified over solar system distances, but the observable universe is 100 billion times larger than that. It requires a leap of faith to believe that our local laws of gravity hold everywhere. Some of the evidence for dark matter relies upon comparing the observed acceleration of objects far apart to that expected from the inverse square law. If the law of universal gravity is invalid for very small accelerations, as proposed in the MOND (Modified Newtonian Dynamics) theory, then our expectations for the interactions of distant objects would change.

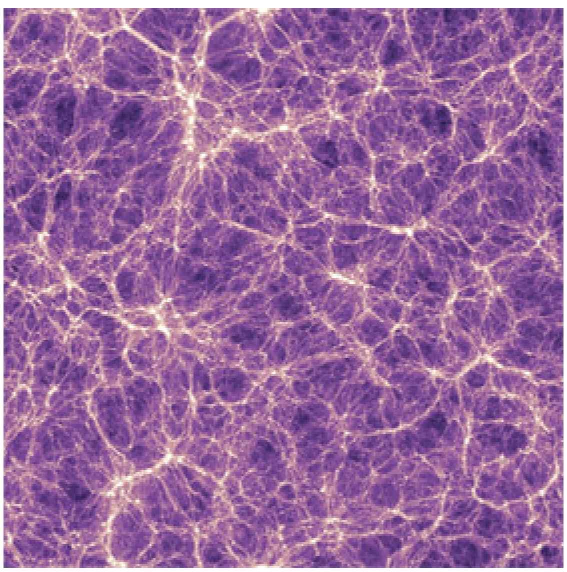


Figure 27: Simulations of structure formation in the universe show the influence of gravity and dark energy.
Source: © Raul Angulo, Max Planck Institute for Astrophysics.

Dark energy, described in detail in Unit 11, has been proposed to explain why the expansion rate of the universe appears to be accelerating. The evidence for dark energy rests upon the comparison of observations with the predictions of general relativity applied to very large length scales. Theorists continue to explore a variety of ways to modify general relativity to circumvent the need for dark energy. As there is no direct experimental evidence one way or another, the behavior of gravity and very large length scales is still an open question.

The first unification in physics was Newton's law of universal gravitation that provided a common explanation for the motion of terrestrial and heavenly objects. It is ironic that for modern attempts to unify all of the forces in nature, gravity is the last and most difficult force to include. The theory of general relativity was a triumph of 20th century physics that revolutionized our concepts of space and time. Yet, even general relativity is not likely to be the ultimate theory of gravity. There is still much to be learned about gravity.

Section 9: Further Reading

- Avery Broderick and Abraham Loeb, "Portrait of a Black Hole," *Scientific American*, December 2009, p. 42.
- George Gamov, "Gravity," Dover Publications, Inc., 2002.
- GRACE Mission website: http://www.csr.utexas.edu/grace/.
- Eduardo Gueron, "Adventures in Curved Spacetime," *Scientific American*, August 2009, p. 38.
- Pankaj S. Joshi, "Naked Singularities," *Scientific American*, February 2009, p. 36.
- Jerzy Jurkiewicz, Renate Loll, and Jan Ambjorn, "The Self-Organizing Quantum Universe," *Scientific American*, July 2008, p. 42.
- Laser Interferometer Gravitational Wave Observatory (LIGO) website: http://www.ligo.caltech.edu/.

Glossary

black hole: A black hole is a region of space where gravity is so strong that nothing can escape its pull. Black holes have been detected through their gravitational influence on nearby stars and through observations of hot gas from surrounding regions accelerating toward them. These black holes are thought to have formed when massive stars reached the end of their cycle of evolution and collapsed under the influence of gravity. If a small volume of space contains enough mass, general relativity predicts that spacetime will become so highly curved that a black hole will form.

cosmic microwave background: The cosmic microwave background (CMB) radiation is electromagnetic radiation left over from when atoms first formed in the early universe, according to our standard model of cosmology. Prior to that time, photons and the fundamental building blocks of matter formed a hot, dense soup, constantly interacting with one another. As the universe expanded and cooled, protons and neutrons formed atomic nuclei, which then combined with electrons to form neutral atoms. At this point, the photons effectively stopped interacting with them. These photons, which have stretched as the universe expanded, form the CMB. First observed by Penzias and Wilson in 1965, the CMB remains the focus of increasingly precise observations intended to provide insight into the composition and evolution of the universe.

Coulomb's Law: Coulomb's Law states that the electric force between two charged particles is proportional to the product of the two charges divided by the square of the distance between the particles.

Doppler shift (Doppler effect): The Doppler shift is a shift in the wavelength of light or sound that depends on the relative motion of the source and the observer. A familiar example of a Doppler shift is the apparent change in pitch of an ambulance siren as it passes a stationary observer. When the ambulance is moving toward the observer, the observer hears a higher pitch because the wavelength of the sound waves is shortened. As the ambulance moves away from the observer, the wavelength is lengthened and the observer hears a lower pitch. Likewise, the wavelength of light emitted by an object moving toward an observer is shortened, and the observer will see a shift to blue. If the light-emitting object is moving away from the observer, the light will have a longer wavelength and the observer will see a shift to red. By observing this shift to red or blue, astronomers can determine the velocity of distant stars and galaxies relative to the Earth. Atoms moving relative to a laser also experience a Doppler shift, which must be taken into account in atomic physics experiments that make use of laser cooling and trapping.

ether: In the late nineteenth century, physicists were putting what they thought were the finishing touches on their theoretical description of electricity and magnetism. In the theory, electromagnetic waves traveled through a medium called "luminiferous ether" just as sound waves travel through the air, or the seismic waves that we experience as earthquakes travel through the Earth. The last remaining detail was to detect the ether and understand its properties. In 1887, Albert Michelson and Edward Morley performed an experiment, verified by many others, that demonstrated that light does not travel through ether. The lack of ether was one of many factors leading Einstein to develop special relativity.

event horizon: A black hole's event horizon is the point of no return for matter falling toward the black hole. Once matter enters the event horizon, it is gravitationally bound to the black hole and cannot escape. However, an external observer will not see the matter enter the black hole. Instead, the gravitational redshift due to the black hole's strong gravitational field causes the object to appear to approach the horizon increasingly slowly without ever going beyond it. Within the event horizon, the black hole's gravitational field warps spacetime so much that even light cannot escape.

general relativity: General relativity is the theory Einstein developed to reconcile gravity with special relativity. While special relativity accurately describes the laws of physics in inertial reference frames, it does not describe what happens in an accelerated reference frame or gravitational field. Since acceleration and gravity are important parts of our physical world, Einstein recognized that special relativity was an incomplete description and spent the years between 1905 and 1915 developing general relativity. In general relativity, we inhabit a four-dimensional spacetime with a curvature determined by the distribution of matter and energy in space. General relativity makes unique, testable predictions that have been upheld by experimental measurements, including the precession of Mercury's orbit, gravitational lensing, and gravitational time dilation. Other predictions of general relativity, including gravitational waves, have not yet been verified. While there is no direct experimental evidence that conflicts with general relativity, the accepted view is that general relativity is an approximation to a more fundamental theory of gravity that will unify it with the Standard Model. See: gravitational lensing. gravitational time dilation, gravitational wave, precession, spacetime, special relativity, Standard Model.

gravitational lensing: Gravitational lensing occurs when light travels past a very massive object. According to Einstein's theory of general relativity, mass shapes spacetime and space is curved by massive objects. Light traveling past a massive object follows a "straight" path in the curved space, and is deflected as if it had passed through a lens. Strong gravitational lensing can cause stars to appear as rings as their light travels in a curved path past a massive object along the line of sight. We observe microlensing when an object such as a MACHO moves between the Earth and a star. The gravitational lens associated with the MACHO focuses the star' light, so we observe the star grow brighter then dimmer as the MACHO moves across our line of sight to the star.

gravitational mass: The gravitational mass of a particle is the gravitational equivalent of electric charge: the physical property of an object that causes it to interact with other objects through the gravitational force. According to the equivalence principle, gravitational mass is equivalent to inertial mass. See: equivalence principle, inertial mass.

gravitational time dilation: Clocks in a strong gravitational field run slower than clocks in a weaker gravitational field. This effect, predicted by Einstein's theory of general relativity and confirmed by precision experiments both on Earth and in space, is called "gravitational time dilation."

Hertz: Hertz (Hz) is a unit of frequency, defined as the number of complete cycles of a periodic signal that take place in one second. For example, the frequency of sound waves is usually reported in units of Hertz. The normal range of human hearing is roughly 20–20,000 Hz. Radio waves have frequencies of thousands of Hz, and light waves in the visible part of the spectrum have frequencies of over 10^{14} Hz.

inertial mass: Inertia is the measure of an object's reluctance to accelerate under an applied force. The inertial mass of an object is the mass that appears in Newton's second law: the acceleration of an object is equal to the applied force divided by its inertial mass. The more inertial mass an object has, the less it accelerates under a fixed applied force. See: equivalence principle, gravitational mass.

MOND: MOND, or Modified Newtonian Dynamics, is a theory that attempts to explain the evidence for dark matter as a modification to Newtonian gravity. There are many versions of the theory, all based on the premise that Newton's laws are slightly different at very small accelerations. A ball dropped above the surface of the Earth would not deviate noticeably from the path predicted by Newtonian physics, but the stars at the very edges of our galaxy would clearly demonstrate modified dynamics if MOND were correct.

Newton's law of universal gravitation: Newton's law of universal gravitation states that the gravitational force between two massive particles is proportional to the product of the two masses divided by the square of the distance between them. The law of universal gravitation is sometimes called the "inverse square law." See: universal gravitational constant.

polarization: The polarization of a wave is the direction in which it is oscillating. The simplest type of polarization is linear, transverse polarization. Linear means that the wave oscillation is confined along a single axis, and transverse means that the wave is oscillating in a direction perpendicular to its direction of travel. Laser light is most commonly a wave with linear, transverse polarization. If the laser beam travels along the x-axis, its electric field will oscillate either in the y-direction or in the z-direction. Gravitational waves also have transverse polarization, but have a more complicated oscillation pattern than laser light.

precession: Precession is a systematic change in the orientation of a rotation axis. For example, the orbits of planets in our solar system precess. Each planet follows an elliptical path around the Sun, with the Sun at one of the focal points of the ellipse. The long axis of the ellipse slowly rotates in the plane of the orbit with the Sun as a pivot point, so the planet never follows exactly the same path through space as it continues to orbit in its elliptical path. The precession measured in Mercury's orbit was found to be different from the prediction of Newtonian gravity but matched the prediction of general relativity, providing some of the first concrete evidence that Einstein's version of gravity is correct.

pulsar: A pulsar is a spinning neutron star with a strong magnetic field that emits electromagnetic radiation along its magnetic axis. Because the star's rotation axis is not aligned with its magnetic axis, we observe pulses of radiation as the star's magnetic axis passes through our line of sight. The time between pulses ranges from a few milliseconds to a few seconds, and tends to slow down over time.

spacetime: In classical physics, space and time are considered separate things. Space is three-dimensional, and can be divided into a three-dimensional grid of cubes that describes the Euclidean geometry familiar from high-school math class. Time is one-dimensional in classical physics. Einstein's theory of special relativity combines the three dimensions of space and one dimension of time into a four-dimensional grid called "spacetime." Spacetime may be flat, in which case Euclidean geometry describes the three space dimensions, or curved. In Einstein's theory of general relativity, the distribution of matter and energy in the universe determines the curvature of spacetime.

special relativity: Einstein developed his theory of special relativity in 1905, 10 years before general relativity. Special relativity is predicated on two postulates. First, the speed of light is assumed to be constant in all inertial frames. Second, the laws of physics are assumed to be the same in all inertial frames. An inertial frame, in this context, is defined as a reference frame that is not accelerating or in a gravitational field. Starting from these two postulates, Einstein derived a number of counterintuitive consequences that were later verified by experiment. Among them are time dilation (a moving clock will run slower than a stationary clock), length contraction (a moving ruler will be shorter than a stationary ruler), the equivalence of mass and energy, and that nothing can move faster than the speed of light. See: general relativity, spacetime.

standard model of cosmology: Our best model for how the universe began and evolved into what we observe now is called the "standard model of cosmology." It contends that the universe began in a Big Bang around 14 billion years ago, which was followed by a short period of exponential inflation. At the end of inflation, quarks, photons, and other fundamental particles formed a hot, dense soup that cooled as the universe continued to expand. Roughly 390,000 years after the end of inflation, the first atoms formed and the cosmic microwave background photons decoupled. Over the course of billions of years, the large structures and astronomical objects we observe throughout the cosmos formed as the universe continued to expand. Eventually the expansion rate of the universe started to increase under the influence of dark energy.

torsion pendulum: A conventional pendulum is a mass suspended on a string that swings periodically. A torsion pendulum is a mass suspended on a string (or torsion fiber) that rotates periodically. When the mass of a torsion pendulum is rotated from its equilibrium position, the fiber resists the rotation and provides a restoring force that causes the mass to rotate back to its original equilibrium position. When the mass reaches its equilibrium position, it is moving quickly and overshoots. The fiber's restoring force, which is proportional to the rotation angle of the mass, eventually causes the mass to slow down and rotate back the other way. Because the restoring force of the torsion fiber is very small, a torsion pendulum can be used to measure extremely small forces affecting the test mass.

universal gravitational constant: The universal gravitational constant, denoted by G, is the proportionality constant in Newton's law of universal gravitation. The currently accepted value for G is $6.67428 \pm 0.00067 \times 10^{-11}$ N-m^2/kg^2.

universality of free fall: The universality of free fall, sometimes abbreviated UFF, is the idea that all materials fall at the same rate in a uniform gravitational field. This is equivalent to stating that inertial and gravitational mass are the same. See: equivalence principle, gravitational mass, inertial mass.