[Template:Other uses](/wiki/Template:Other_uses" \o "Template:Other uses) [Template:Redirect4](/wiki/Template:Redirect4) [Template:Pp-move-indef](/wiki/Template:Pp-move-indef) [Template:Use dmy dates](/wiki/Template:Use_dmy_dates) [Template:Refimprove](/wiki/Template:Refimprove) [right|thumb|Hammer and feather drop:](/wiki/File:Apollo_15_feather_and_hammer_drop.ogg) [Apollo 15](/wiki/Apollo_15) [astronaut](/wiki/Astronaut) [David Scott](/wiki/David_Scott) on the Moon enacting the legend of Galileo's gravity experiment. (1.38 [MB](/wiki/Megabyte), [ogg](/wiki/Ogg)/[Theora](/wiki/Theora) format). **Gravity** or **gravitation** is a [natural phenomenon](/wiki/Natural_phenomenon) by which all things with [energy](/wiki/Energy) are brought toward (or *gravitate* toward) one another, including [stars](/wiki/Star), [planets](/wiki/Planet), [galaxies](/wiki/Galaxies) and even [light](/wiki/Light) and [sub-atomic particles](/wiki/Sub-atomic_particles). Gravity is responsible for many of the structures in the [Universe](/wiki/Universe), by creating spheres of [hydrogen](/wiki/Hydrogen) — where hydrogen fuses under pressure to form stars — and grouping them into galaxies. On [Earth](/wiki/Earth), gravity gives [weight](/wiki/Weight) to physical objects and causes the tides. Gravity has an infinite range, although its effects become increasingly weaker on farther objects.

Gravity is most accurately described by the [general theory of relativity](/wiki/General_theory_of_relativity) (proposed by [Albert Einstein](/wiki/Albert_Einstein) in 1915) which describes gravity not as a [force](/wiki/Force) but as a consequence of the curvature of [spacetime](/wiki/Spacetime) caused by the uneven distribution of [mass](/wiki/Mass)/[energy](/wiki/Energy); and resulting in [gravitational time dilation](/wiki/Gravitational_time_dilation), where time lapses more slowly in lower (stronger) [gravitational potential](/wiki/Gravitational_potential). However, for most applications, gravity is well approximated by [Newton's law of universal gravitation](/wiki/Newton's_law_of_universal_gravitation), which postulates that gravity causes a [force](/wiki/Force) where two bodies of mass are directly drawn (or 'attracted') to each other according to a mathematical relationship, where the attractive force is [proportional](/wiki/Proportionality_(mathematics)) to the product of their masses and [inversely proportional](/wiki/Inversely_proportional) to the [square](/wiki/Square_(algebra)) of the [distance](/wiki/Distance) between them. This is considered[Template:By whom](/wiki/Template:By_whom) to occur over an infinite range, such that all bodies (with mass) in the universe are drawn to each other no matter how far they are apart.[Template:Citation needed](/wiki/Template:Citation_needed)

Gravity is the weakest of the four [fundamental interactions](/wiki/Fundamental_interaction) of nature. The gravitational attraction is approximately 10−38 times the strength of the [strong force](/wiki/Strong_interaction) (i.e. gravity is 38 orders of magnitude weaker), 10−36 times the strength of the [electromagnetic force](/wiki/Electromagnetic_force), and 10−29 times the strength of the [weak force](/wiki/Weak_interaction). As a consequence, gravity has a negligible influence on the behavior of sub-atomic particles, and plays no role in determining the internal properties of everyday matter (but see [quantum gravity](/wiki/Quantum_gravity)). On the other hand, gravity is the dominant interaction at the [macroscopic scale](/wiki/Macroscopic_scale), and is the cause of the formation, shape, and [trajectory](/wiki/Trajectory) ([orbit](/wiki/Orbit)) of astronomical bodies. It is responsible for various phenomena observed on Earth and throughout the universe; for example, it causes the Earth and the other planets to orbit the Sun, the [Moon](/wiki/Moon) to orbit the Earth, the formation of [tides](/wiki/Tide), and the formation and evolution of [galaxies](/wiki/Galaxy_formation_and_evolution), [stars](/wiki/Stellar_evolution) and the [Solar System](/wiki/Formation_and_evolution_of_the_Solar_System).

In pursuit of a [theory of everything](/wiki/Theory_of_everything), the merging of general relativity and [quantum mechanics](/wiki/Quantum_mechanics) (or [quantum field theory](/wiki/Quantum_field_theory)) into a more general theory of [quantum gravity](/wiki/Quantum_gravity) has become an area of research.

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## History of gravitational theory[[edit](/index.php?title=(none)&action=edit&section=1)]

[Template:Main](/wiki/Template:Main) [Template:Classical mechanics](/wiki/Template:Classical_mechanics)

### Scientific revolution[[edit](/index.php?title=(none)&action=edit&section=2)]

Modern work on gravitational theory began with the work of [Galileo Galilei](/wiki/Galileo_Galilei) in the late 16th and early 17th centuries. In his famous (though possibly [apocryphal](/wiki/Apocrypha)<ref name=Ball\_Piza>[Template:Cite journal](/wiki/Template:Cite_journal)</ref>) experiment dropping balls from the [Tower of Pisa](/wiki/Leaning_Tower_of_Pisa), and later with careful measurements of balls rolling down [inclines](/wiki/Inclined_plane), Galileo showed that gravitational acceleration is the same for all objects. This was a major departure from [Aristotle's](/wiki/Aristotle) belief that heavier objects have a higher gravitational acceleration.[[1]](#cite_note-1) Galileo postulated [air resistance](/wiki/Air_resistance) as the reason that objects with less mass may fall slower in an atmosphere. Galileo's work set the stage for the formulation of Newton's theory of gravity.

### Newton's theory of gravitation[[edit](/index.php?title=(none)&action=edit&section=3)]

[Template:Main](/wiki/Template:Main) [thumb|200px|left|](/wiki/File:Sir_Isaac_Newton_(1643-1727).jpg)[Sir Isaac Newton](/wiki/Isaac_Newton), an English physicist who lived from 1642 to 1727 In 1687, English mathematician Sir [Isaac Newton](/wiki/Isaac_Newton) published [*Principia*](/wiki/Philosophiæ_Naturalis_Principia_Mathematica), which hypothesizes the [inverse-square law](/wiki/Inverse-square_law) of universal gravitation. In his own words, "I deduced that the forces which keep the planets in their orbs must [be] reciprocally as the squares of their distances from the centers about which they revolve: and thereby compared the force requisite to keep the Moon in her Orb with the force of gravity at the surface of the Earth; and found them answer pretty nearly."[[2]](#cite_note-2) The equation is the following:

<math>F = G \frac{m\_1 m\_2}{r^2}\ </math>

Where *F* is the force, *m1* and *m2* are the masses of the objects interacting, *r* is the distance between the centers of the masses and *G* is the [gravitational constant](/wiki/Gravitational_constant).

Newton's theory enjoyed its greatest success when it was used to predict the existence of [Neptune](/wiki/Neptune) based on motions of [Uranus](/wiki/Uranus) that could not be accounted for by the actions of the other planets. Calculations by both [John Couch Adams](/wiki/John_Couch_Adams) and [Urbain Le Verrier](/wiki/Urbain_Le_Verrier) predicted the general position of the planet, and Le Verrier's calculations are what led [Johann Gottfried Galle](/wiki/Johann_Gottfried_Galle) to the discovery of Neptune.

A discrepancy in [Mercury's](/wiki/Mercury_(planet)) orbit pointed out flaws in Newton's theory. By the end of the 19th century, it was known that its orbit showed slight perturbations that could not be accounted for entirely under Newton's theory, but all searches for another perturbing body (such as a planet orbiting the [Sun](/wiki/Sun) even closer than Mercury) had been fruitless. The issue was resolved in 1915 by [Albert Einstein's](/wiki/Albert_Einstein) new theory of [general relativity](/wiki/General_relativity), which accounted for the small discrepancy in Mercury's orbit.

Although Newton's theory has been superseded by the [Einstein's](/wiki/Einstein) general relativity, most modern [non-relativistic](/wiki/Theory_of_relativity) gravitational calculations are still made using Newton's theory because it is simpler to work with and it gives sufficiently accurate results for most applications involving sufficiently small masses, speeds and energies.

### Equivalence principle[[edit](/index.php?title=(none)&action=edit&section=4)]

The [equivalence principle](/wiki/Equivalence_principle), explored by a succession of researchers including Galileo, [Loránd Eötvös](/wiki/Loránd_Eötvös), and Einstein, expresses the idea that all objects fall in the same way, and that the effects of gravity are indistinguishable from certain aspects of acceleration and deceleration. The simplest way to test the weak equivalence principle is to drop two objects of different [masses](/wiki/Mass) or compositions in a vacuum and see whether they hit the ground at the same time. Such experiments demonstrate that all objects fall at the same rate when other forces (such as air resistance and electromagnetic effects) are negligible. More sophisticated tests use a torsion balance of a type invented by Eötvös. Satellite experiments, for example [STEP](/wiki/STEP_(satellite)), are planned for more accurate experiments in space.[[3]](#cite_note-3) Formulations of the equivalence principle include:

* The weak equivalence principle: *The trajectory of a point mass in a* [*gravitational field*](/wiki/Gravitational_field) *depends only on its initial position and velocity, and is independent of its composition.*<ref name=Wesson>[Template:Cite book](/wiki/Template:Cite_book)</ref>
* The Einsteinian equivalence principle: *The outcome of any local non-gravitational experiment in a freely falling laboratory is independent of the velocity of the laboratory and its location in spacetime.*[[4]](#cite_note-4)\* The strong equivalence principle requiring both of the above.

### General relativity[[edit](/index.php?title=(none)&action=edit&section=5)]

[Template:See also](/wiki/Template:See_also) [thumb|300px|right|Two-dimensional analogy of spacetime distortion generated by the mass of an object. Matter changes the geometry of spacetime, this (curved) geometry being interpreted as gravity. White lines do not represent the curvature of space but instead represent the](/wiki/File:GPB_circling_earth.jpg) [coordinate system](/wiki/Coordinate_system) imposed on the curved spacetime, which would be [rectilinear](/wiki/Regular_grid) in a flat spacetime. [Template:General relativity sidebar](/wiki/Template:General_relativity_sidebar) In [general relativity](/wiki/General_relativity), the effects of gravitation are ascribed to [spacetime](/wiki/Spacetime) [curvature](/wiki/Curvature) instead of a force. The starting point for general relativity is the [equivalence principle](/wiki/Equivalence_principle), which equates free fall with inertial motion and describes free-falling inertial objects as being accelerated relative to non-inertial observers on the ground.[[5]](#cite_note-5)[[6]](#cite_note-6) In [Newtonian physics](/wiki/Newtonian_physics), however, no such acceleration can occur unless at least one of the objects is being operated on by a force.

Einstein proposed that spacetime is curved by matter, and that free-falling objects are moving along locally straight paths in curved spacetime. These straight paths are called [geodesics](/wiki/Geodesic_(general_relativity)). Like Newton's first law of motion, Einstein's theory states that if a force is applied on an object, it would deviate from a geodesic. For instance, we are no longer following geodesics while standing because the mechanical resistance of the Earth exerts an upward force on us, and we are non-inertial on the ground as a result. This explains why moving along the geodesics in spacetime is considered inertial.

Einstein discovered the [field equations](/wiki/Field_equation) of general relativity, which relate the presence of matter and the curvature of spacetime and are named after him. The [Einstein field equations](/wiki/Einstein_field_equations) are a set of 10 [simultaneous](/wiki/Simultaneous_equations), [non-linear](/wiki/Nonlinear_system), [differential equations](/wiki/Differential_equation). The solutions of the field equations are the components of the [metric tensor](/wiki/Metric_tensor_(general_relativity)) of spacetime. A metric tensor describes a geometry of spacetime. The geodesic paths for a spacetime are calculated from the metric tensor.

#### Solutions[[edit](/index.php?title=(none)&action=edit&section=6)]

Notable solutions of the Einstein field equations include:

* The [Schwarzschild solution](/wiki/Schwarzschild_solution), which describes spacetime surrounding a [spherically symmetric](/wiki/Circular_symmetry) non-[rotating](/wiki/Rotation) uncharged massive object. For compact enough objects, this solution generated a [black hole](/wiki/Black_hole) with a central [singularity](/wiki/Gravitational_singularity). For radial distances from the center which are much greater than the [Schwarzschild radius](/wiki/Schwarzschild_radius), the accelerations predicted by the Schwarzschild solution are practically identical to those predicted by Newton's theory of gravity.
* The [Reissner-Nordström solution](/wiki/Reissner–Nordström_metric), in which the central object has an electrical charge. For charges with a [geometrized](/wiki/Geometrized) length which are less than the geometrized length of the mass of the object, this solution produces black holes with two [event horizons](/wiki/Event_horizon).
* The [Kerr solution](/wiki/Kerr_metric) for rotating massive objects. This solution also produces black holes with multiple event horizons.
* The [Kerr-Newman solution](/wiki/Kerr–Newman_metric) for charged, rotating massive objects. This solution also produces black holes with multiple event horizons.
* The [cosmological](/wiki/Physical_cosmology) [Friedmann-Lemaître-Robertson-Walker solution](/wiki/Friedmann–Lemaître–Robertson–Walker_metric), which predicts the expansion of the [universe](/wiki/Universe).

#### Tests[[edit](/index.php?title=(none)&action=edit&section=7)]

The [tests of general relativity](/wiki/Tests_of_general_relativity) included the following:<ref name=Pauli1958>[Template:Cite book](/wiki/Template:Cite_book)</ref>

* General relativity accounts for the anomalous [perihelion precession of Mercury](/wiki/Perihelion_precession_of_Mercury).[[7]](#cite_note-7)\* The prediction that time runs slower at lower potentials ([gravitational time dilation](/wiki/Gravitational_time_dilation)) has been confirmed by the [Pound–Rebka experiment](/wiki/Pound–Rebka_experiment) (1959), the [Hafele–Keating experiment](/wiki/Hafele–Keating_experiment), and the [GPS](/wiki/GPS#Predecessors).
* The prediction of the deflection of light was first confirmed by [Arthur Stanley Eddington](/wiki/Arthur_Stanley_Eddington) from his observations during the [Solar eclipse of May 29, 1919](/wiki/Solar_eclipse_of_May_29,_1919).[[8]](#cite_note-8)[[9]](#cite_note-9) Eddington measured starlight deflections twice those predicted by Newtonian corpuscular theory, in accordance with the predictions of general relativity. However, his interpretation of the results was later disputed.[[10]](#cite_note-10) More recent tests using radio interferometric measurements of [quasars](/wiki/Quasar) passing behind the [Sun](/wiki/Sun) have more accurately and consistently confirmed the deflection of light to the degree predicted by general relativity.[[11]](#cite_note-11) See also [gravitational lens](/wiki/Gravitational_lens).
* The [time delay of light](/wiki/Time_delay_of_light) passing close to a massive object was first identified by [Irwin I. Shapiro](/wiki/Irwin_I._Shapiro) in 1964 in interplanetary spacecraft signals.
* [Gravitational radiation](/wiki/Gravitational_radiation) has been indirectly confirmed through studies of binary [pulsars](/wiki/Pulsar). On 11 February 2016, the [LIGO](/wiki/LIGO) and [Virgo](/wiki/Virgo_interferometer) collaborations announced the first observation of a gravitational wave.
* [Alexander Friedmann](/wiki/Alexander_Friedmann) in 1922 found that Einstein equations have non-stationary solutions (even in the presence of the [cosmological constant](/wiki/Cosmological_constant)). In 1927 [Georges Lemaître](/wiki/Georges_Lemaître) showed that static solutions of the Einstein equations, which are possible in the presence of the cosmological constant, are unstable, and therefore the static universe envisioned by Einstein could not exist. Later, in 1931, Einstein himself agreed with the results of Friedmann and Lemaître. Thus general relativity predicted that the Universe had to be non-static—it had to either expand or contract. The expansion of the universe discovered by [Edwin Hubble](/wiki/Edwin_Hubble) in 1929 confirmed this prediction.<ref name=Pauli1>See W.Pauli, 1958, pp.219–220</ref>
* The theory's prediction of [frame dragging](/wiki/Frame_dragging) was consistent with the recent [Gravity Probe B](/wiki/Gravity_Probe_B) results.[[12]](#cite_note-12)\*General relativity predicts that light should lose its energy when traveling away from massive bodies through [gravitational redshift](/wiki/Gravitational_redshift). This was verified on earth and in the solar system around 1960.

### Gravity and quantum mechanics[[edit](/index.php?title=(none)&action=edit&section=8)]

[Template:Main](/wiki/Template:Main) In the decades after the discovery of general relativity, it was realized that general relativity is incompatible with [quantum mechanics](/wiki/Quantum_mechanics).[[13]](#cite_note-13) It is possible to describe gravity in the framework of [quantum field theory](/wiki/Quantum_field_theory) like the other [fundamental forces](/wiki/Fundamental_forces), such that the attractive force of gravity arises due to exchange of [virtual](/wiki/Virtual_particle) gravitons, in the same way as the electromagnetic force arises from exchange of virtual [photons](/wiki/Photon).[[14]](#cite_note-14)[[15]](#cite_note-15) This reproduces general relativity in the [classical limit](/wiki/Classical_limit). However, this approach fails at short distances of the order of the [Planck length](/wiki/Planck_length),[[13]](#cite_note-13) where a more complete theory of [quantum gravity](/wiki/Quantum_gravity) (or a new approach to quantum mechanics) is required.

## Specifics[[edit](/index.php?title=(none)&action=edit&section=9)]

[Template:Nature timeline](/wiki/Template:Nature_timeline)

### Earth's gravity[[edit](/index.php?title=(none)&action=edit&section=10)]

[Template:Main](/wiki/Template:Main) Every planetary body (including the Earth) is surrounded by its own gravitational field, which can be conceptualized with Newtonian physics as exerting an attractive force on all objects. Assuming a spherically symmetrical planet, the strength of this field at any given point above the surface is proportional to the planetary body's mass and inversely proportional to the square of the distance from the center of the body. [thumb|150px|left|If an object with comparable mass to that of the Earth were to fall towards it, then the corresponding acceleration of the Earth would be observable.](/wiki/File:Gravity_action-reaction.gif) The strength of the gravitational field is numerically equal to the acceleration of objects under its influence.[Template:Citation needed](/wiki/Template:Citation_needed) The rate of acceleration of falling objects near the Earth's surface varies very slightly depending on latitude, surface features such as mountains and ridges, and perhaps unusually high or low sub-surface densities.[[16]](#cite_note-16) For purposes of weights and measures, a [standard gravity](/wiki/Standard_gravity) value is defined by the [International Bureau of Weights and Measures](/wiki/International_Bureau_of_Weights_and_Measures), under the [International System of Units](/wiki/International_System_of_Units) (SI).

That value, denoted *g*, is *g* = 9.80665 m/s2 (32.1740 ft/s2).[[17]](#cite_note-17)[[18]](#cite_note-18) The standard value of 9.80665 m/s2 is the one originally adopted by the International Committee on Weights and Measures in 1901 for 45° latitude, even though it has been shown to be too high by about five parts in ten thousand.<ref name=List>List, R. J. editor, 1968, Acceleration of Gravity, *Smithsonian Meteorological Tables*, Sixth Ed. Smithsonian Institution, Washington, D.C., p. 68.</ref> This value has persisted in meteorology and in some standard atmospheres as the value for 45° latitude even though it applies more precisely to latitude of 45°32'33".<ref name=USSA1976>[U.S. Standard Atmosphere](http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19770009539_1977009539.pdf), 1976, U.S. Government Printing Office, Washington, D.C., 1976. (Linked file is very large.)</ref>

Assuming the standardized value for g and ignoring air resistance, this means that an object falling freely near the Earth's surface increases its velocity by 9.80665 m/s (32.1740 ft/s or 22 mph) for each second of its descent. Thus, an object starting from rest will attain a velocity of 9.80665 m/s (32.1740 ft/s) after one second, approximately 19.62 m/s (64.4 ft/s) after two seconds, and so on, adding 9.80665 m/s (32.1740 ft/s) to each resulting velocity. Also, again ignoring air resistance, any and all objects, when dropped from the same height, will hit the ground at the same time.

According to [Newton's 3rd Law](/wiki/Newton's_3rd_law), the Earth itself experiences a [force](/wiki/Newtons) equal in magnitude and opposite in direction to that which it exerts on a falling object. This means that the Earth also accelerates towards the object until they collide. Because the mass of the Earth is huge, however, the acceleration imparted to the Earth by this opposite force is negligible in comparison to the object's. If the object doesn't bounce after it has collided with the Earth, each of them then exerts a repulsive [contact force](/wiki/Contact_force) on the other which effectively balances the attractive force of gravity and prevents further acceleration.

The force of gravity on Earth is the resultant (vector sum) of two forces:[Template:Dubious](/wiki/Template:Dubious)[Template:Citation needed](/wiki/Template:Citation_needed) (a) The gravitational attraction in accordance with Newton's universal law of gravitation, and (b) the centrifugal force[Template:Dubious](/wiki/Template:Dubious)[Template:Citation needed](/wiki/Template:Citation_needed), which results from the choice of an earthbound, rotating frame of reference. At the equator, the force of gravity is the weakest due to the centrifugal force caused by the Earth's rotation. The force of gravity varies with latitude and increases from about 9.780 m/s2 at the Equator to about 9.832 m/s2 at the poles.

### Equations for a falling body near the surface of the Earth[[edit](/index.php?title=(none)&action=edit&section=11)]

[Template:Main](/wiki/Template:Main) Under an assumption of constant gravitational attraction, [Newton's law of universal gravitation](/wiki/Newton's_law_of_universal_gravitation) simplifies to *F* = *mg*, where *m* is the [mass](/wiki/Mass) of the body and *g* is a constant vector with an average magnitude of 9.81 m/s2 on Earth. This resulting force is the object's [weight](/wiki/Weight). The acceleration due to gravity is equal to this *g*. An initially stationary object which is allowed to fall freely under gravity drops a distance which is proportional to the square of the elapsed time. The image on the right, spanning half a second, was captured with a stroboscopic flash at 20 flashes per second. During the first [Template:Frac](/wiki/Template:Frac) of a second the ball drops one unit of distance (here, a unit is about 12 mm); by [Template:Frac](/wiki/Template:Frac) it has dropped at total of 4 units; by [Template:Frac](/wiki/Template:Frac), 9 units and so on.

Under the same constant gravity assumptions, the [potential energy](/wiki/Potential_energy), *Ep*, of a body at height *h* is given by *Ep* = *mgh* (or *Ep* = *Wh*, with *W* meaning weight). This expression is valid only over small distances *h* from the surface of the Earth. Similarly, the expression <math>h = \tfrac{v^2}{2g}</math> for the maximum height reached by a vertically projected body with initial velocity *v* is useful for small heights and small initial velocities only.

### Gravity and astronomy[[edit](/index.php?title=(none)&action=edit&section=12)]

[thumb|100px|Ball falling freely under gravity. See text for description.](/wiki/File:Falling_ball.jpg)

[thumb|left|Gravity acts on stars that form our](/wiki/File:Milky_Way_Emerges_as_Sun_Sets_over_Paranal.jpg) [Milky Way](/wiki/Milky_Way).[[19]](#cite_note-19) The application of Newton's law of gravity has enabled the acquisition of much of the detailed information we have about the planets in the Solar System, the mass of the Sun, and details of [quasars](/wiki/Quasar); even the existence of [dark matter](/wiki/Dark_matter) is inferred using Newton's law of gravity. Although we have not traveled to all the planets nor to the Sun, we know their masses. These masses are obtained by applying the laws of gravity to the measured characteristics of the orbit. In space an object maintains its [orbit](/wiki/Orbit) because of the force of gravity acting upon it. Planets orbit stars, stars orbit [galactic centers](/wiki/Bulge_(astronomy)), [galaxies](/wiki/Galaxy) orbit a center of mass in clusters, and clusters orbit in [superclusters](/wiki/Supercluster). The force of gravity exerted on one object by another is directly proportional to the product of those objects' masses and inversely proportional to the square of the distance between them.

### Gravitational radiation[[edit](/index.php?title=(none)&action=edit&section=13)]

[Template:Main](/wiki/Template:Main) According to general relativity, gravitational radiation is generated in situations where the curvature of [spacetime](/wiki/Spacetime) is oscillating, such as is the case with co-orbiting objects. The gravitational radiation emitted by the [Solar System](/wiki/Solar_System) is far too small to measure. However, gravitational radiation has been indirectly observed as an energy loss over time in binary pulsar systems such as [PSR B1913+16](/wiki/PSR_B1913+16). It is believed that [neutron star](/wiki/Neutron_star) mergers and [black hole](/wiki/Black_hole) formation may create detectable amounts of gravitational radiation. Gravitational radiation observatories such as the Laser Interferometer Gravitational Wave Observatory ([LIGO](/wiki/LIGO)) have been created to study the problem. In February 2016, the Advanced LIGO team announced that they had detected gravitational waves from a black hole collision. On September 14, 2015 LIGO registered gravitational waves for the first time, as a result of the collision of two black holes 1.3 billion light-years from Earth.[[20]](#cite_note-20)[[21]](#cite_note-21) This observation confirms the theoretical predictions of Einstein and others that such waves exist. The event confirms that [binary black holes](/wiki/Binary_black_hole) exist. It also opens the way for practical observation and understanding of the nature of gravity and events in the Universe including the Big Bang and what happened after it.[[22]](#cite_note-22)[[23]](#cite_note-23)

### Speed of gravity[[edit](/index.php?title=(none)&action=edit&section=14)]

[Template:Main](/wiki/Template:Main) In December 2012, a research team in China announced that it had produced measurements of the phase lag of [Earth tides](/wiki/Earth_tide) during full and new moons which seem to prove that the speed of gravity is equal to the speed of light.[[24]](#cite_note-24) This means that if the Sun suddenly disappeared, the Earth would keep orbiting it normally for 8 minutes, which is the time light takes to travel that distance. The team's findings were released in the [Chinese Science Bulletin](/wiki/Chinese_Science_Bulletin) in February 2013.[[25]](#cite_note-25)

## Anomalies and discrepancies[[edit](/index.php?title=(none)&action=edit&section=15)]

There are some observations that are not adequately accounted for, which may point to the need for better theories of gravity or perhaps be explained in other ways. [frame|right|Rotation curve of a typical spiral galaxy: predicted (**A**) and observed (**B**). The discrepancy between the curves is attributed to](/wiki/File:GalacticRotation2.svg) [dark matter](/wiki/Dark_matter).

* **Extra-fast stars**: Stars in galaxies follow a [distribution of velocities](/wiki/Galaxy_rotation_curve) where stars on the outskirts are moving faster than they should according to the observed distributions of normal matter. Galaxies within [galaxy clusters](/wiki/Galaxy_groups_and_clusters) show a similar pattern. [Dark matter](/wiki/Dark_matter), which would interact through gravitation but not electromagnetically, would account for the discrepancy. Various [modifications to Newtonian dynamics](/wiki/Modified_Newtonian_dynamics) have also been proposed.
* [**Flyby anomaly**](/wiki/Flyby_anomaly): Various spacecraft have experienced greater acceleration than expected during [gravity assist](/wiki/Gravity_assist) maneuvers.
* **Accelerating expansion**: The [metric expansion of space](/wiki/Metric_expansion_of_space) seems to be speeding up. [Dark energy](/wiki/Dark_energy) has been proposed to explain this. A recent alternative explanation is that the geometry of space is not homogeneous (due to clusters of galaxies) and that when the data are reinterpreted to take this into account, the expansion is not speeding up after all,[[26]](#cite_note-26) however this conclusion is disputed.[[27]](#cite_note-27)\* **Anomalous increase of the** [**astronomical unit**](/wiki/Astronomical_unit): Recent measurements indicate that [planetary orbits are widening](/wiki/Astronomical_unit#Developments) faster than if this were solely through the Sun losing mass by radiating energy.
* **Extra energetic photons**: Photons travelling through galaxy clusters should gain energy and then lose it again on the way out. The accelerating expansion of the universe should stop the photons returning all the energy, but even taking this into account photons from the [cosmic microwave background radiation](/wiki/Cosmic_microwave_background_radiation) gain twice as much energy as expected. This may indicate that gravity falls off *faster* than inverse-squared at certain distance scales.<ref name=newsci2699>[Template:Cite web](/wiki/Template:Cite_web)</ref>
* **Extra massive hydrogen clouds**: The spectral lines of the [Lyman-alpha forest](/wiki/Lyman-alpha_forest) suggest that hydrogen clouds are more clumped together at certain scales than expected and, like [dark flow](/wiki/Dark_flow), may indicate that gravity falls off *slower* than inverse-squared at certain distance scales.<ref name=newsci2699/>
* **Power**: Proposed [extra dimensions](/wiki/Extra_dimensions) could explain why the gravity force is so weak.[[28]](#cite_note-28)

## Alternative theories[[edit](/index.php?title=(none)&action=edit&section=16)]

[Template:Main](/wiki/Template:Main)

### Historical alternative theories[[edit](/index.php?title=(none)&action=edit&section=17)]

* [Aristotelian theory of gravity](/wiki/Aristotelian_theory_of_gravity)
* [Le Sage's theory of gravitation](/wiki/Le_Sage's_theory_of_gravitation) (1784) also called LeSage gravity, proposed by [Georges-Louis Le Sage](/wiki/Georges-Louis_Le_Sage), based on a fluid-based explanation where a light gas fills the entire universe.
* [Ritz's theory of gravitation](/wiki/Ritz's_Equation), *Ann. Chem. Phys.* 13, 145, (1908) pp. 267–271, Weber-Gauss electrodynamics applied to gravitation. Classical advancement of perihelia.
* [Nordström's theory of gravitation](/wiki/Nordström's_theory_of_gravitation) (1912, 1913), an early competitor of general relativity.
* [Kaluza Klein theory](/wiki/Kaluza–Klein_theory) (1921)
* [Whitehead's theory of gravitation](/wiki/Whitehead's_theory_of_gravitation) (1922), another early competitor of general relativity.

### Modern alternative theories[[edit](/index.php?title=(none)&action=edit&section=18)]

* [Brans–Dicke theory](/wiki/Brans–Dicke_theory) of gravity (1961) <ref name=2014Schpj...931358B>[Template:Cite journal](/wiki/Template:Cite_journal)</ref>
* [Induced gravity](/wiki/Induced_gravity) (1967), a proposal by [Andrei Sakharov](/wiki/Andrei_Sakharov) according to which [general relativity](/wiki/General_relativity) might arise from [quantum field theories](/wiki/Quantum_field_theory) of matter
* [ƒ(R) gravity](/wiki/F(R)_gravity) (1970)
* [Horndeski theory](/wiki/Horndeski_theory) (1974) <ref name=1974IJTP...10..363H>[Template:Cite journal](/wiki/Template:Cite_journal)</ref>
* [Supergravity](/wiki/Supergravity) (1976)
* [String theory](/wiki/String_theory)
* In the [modified Newtonian dynamics](/wiki/Modified_Newtonian_dynamics) (MOND) (1981), [Mordehai Milgrom](/wiki/Mordehai_Milgrom) proposes a modification of [Newton's Second Law](/wiki/Newton's_Second_Law) of motion for small accelerations <ref name=2014SchpJ...931410M>[Template:Cite journal](/wiki/Template:Cite_journal)</ref>
* The [self-creation cosmology](/wiki/Self-creation_cosmology) theory of gravity (1982) by G.A. Barber in which the Brans-Dicke theory is modified to allow mass creation
* [Loop quantum gravity](/wiki/Loop_quantum_gravity) (1988) by [Carlo Rovelli](/wiki/Carlo_Rovelli), [Lee Smolin](/wiki/Lee_Smolin), and [Abhay Ashtekar](/wiki/Abhay_Ashtekar)
* [Nonsymmetric gravitational theory](/wiki/Nonsymmetric_gravitational_theory) (NGT) (1994) by [John Moffat](/wiki/John_Moffat_(physicist))
* [Conformal gravity](/wiki/Conformal_gravity)[[29]](#cite_note-29)\* [Tensor–vector–scalar gravity](/wiki/Tensor–vector–scalar_gravity) (TeVeS) (2004), a relativistic modification of MOND by [Jacob Bekenstein](/wiki/Jacob_Bekenstein)
* [Gravity as an entropic force](/wiki/Gravity_as_an_entropic_force), gravity arising as an emergent phenomenon from the thermodynamic concept of entropy.
* In the [superfluid vacuum theory](/wiki/Superfluid_vacuum_theory) the gravity and curved space-time arise as a [collective excitation](/wiki/Collective_excitation) mode of non-relativistic background [superfluid](/wiki/Superfluid).
* [Chameleon theory](/wiki/Chameleon_particle) (2004) by [Justin Khoury](/wiki/Justin_Khoury) and [Amanda Weltman](/wiki/Amanda_Weltman).
* [Pressuron theory](/wiki/Pressuron) (2013) by [Olivier Minazzoli](/wiki/Olivier_Minazzoli) and [Aurélien Hees](/wiki/Aurélien_Hees).

## See also[[edit](/index.php?title=(none)&action=edit&section=19)]

[Template:Div col](/wiki/Template:Div_col)

* [Angular momentum](/wiki/Angular_momentum)
* [Anti-gravity](/wiki/Anti-gravity), the idea of neutralizing or repelling gravity
* [Artificial gravity](/wiki/Artificial_gravity)
* [Birkeland current](/wiki/Birkeland_current)
* [Cosmic gravitational wave background](/wiki/Cosmic_gravitational_wave_background)
* [Einstein–Infeld–Hoffmann equations](/wiki/Einstein–Infeld–Hoffmann_equations)
* [Escape velocity](/wiki/Escape_velocity), the minimum velocity needed to escape from a [gravity well](/wiki/Gravity_well)
* [g-force](/wiki/G-force), a measure of [acceleration](/wiki/Acceleration)
* [Gauge gravitation theory](/wiki/Gauge_gravitation_theory)
* [Gauss's law for gravity](/wiki/Gauss's_law_for_gravity)
* [Gravitational binding energy](/wiki/Gravitational_binding_energy)
* [Gravitational wave](/wiki/Gravitational_wave)
* [Gravitational wave background](/wiki/Gravitational_wave_background)
* [Gravity assist](/wiki/Gravity_assist)
* [Gravity gradiometry](/wiki/Gravity_gradiometry)
* [Gravity Recovery and Climate Experiment](/wiki/Gravity_Recovery_and_Climate_Experiment)
* [Gravity Research Foundation](/wiki/Gravity_Research_Foundation)
* [Jovian–Plutonian gravitational effect](/wiki/Jovian–Plutonian_gravitational_effect)
* [Kepler's third law of planetary motion](/wiki/Kepler's_third_law)
* [Lagrangian point](/wiki/Lagrangian_point)
* [Micro-g environment](/wiki/Micro-g_environment), also called microgravity
* [Mixmaster dynamics](/wiki/Mixmaster_dynamics)
* [*n*-body problem](/wiki/N-body_problem)
* [Newton's laws of motion](/wiki/Newton's_laws_of_motion)
* [Pioneer anomaly](/wiki/Pioneer_anomaly)
* [Scalar theories of gravitation](/wiki/Scalar_theories_of_gravitation)
* [Speed of gravity](/wiki/Speed_of_gravity)
* [Standard gravitational parameter](/wiki/Standard_gravitational_parameter)
* [Standard gravity](/wiki/Standard_gravity)
* [Weightlessness](/wiki/Weightlessness)

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## Footnotes[[edit](/index.php?title=(none)&action=edit&section=20)]

[Template:Reflist](/wiki/Template:Reflist)

## References[[edit](/index.php?title=(none)&action=edit&section=21)]

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* [Template:Cite book](/wiki/Template:Cite_book)
* [Template:Cite book](/wiki/Template:Cite_book)
* [Template:Cite book](/wiki/Template:Cite_book)

[Template:Refend](/wiki/Template:Refend)

## Further reading[[edit](/index.php?title=(none)&action=edit&section=22)]

* [Template:Cite book](/wiki/Template:Cite_book)

## External links[[edit](/index.php?title=(none)&action=edit&section=23)]

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* [Template:Springer](/wiki/Template:Springer)
* [Template:Springer](/wiki/Template:Springer)

[Template:Fundamental interactions](/wiki/Template:Fundamental_interactions) [Template:Theories of gravitation](/wiki/Template:Theories_of_gravitation) [Template:Authority control](/wiki/Template:Authority_control) [Template:Portal bar](/wiki/Template:Portal_bar)

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