

General Theory of Relativity

Ck12 Science

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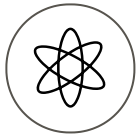
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AUTHORS

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General Theory of Relativity

Explains how gravity affects space and time.

General Theory of Relativity



The mission of NASA's Chandra X-ray Observatory is to detect X-ray emission from the hottest regions of the Universe such as the high-energy gas swirling around a black hole.

The General Theory of Relativity

In 1905, Albert Einstein published the theory of special relativity, a theory about space and time. In the following years, Einstein worked on the fact that acceleration produced the same effect as gravitation. For example, if you were in an accelerating spaceship, or just an elevator, you could not tell if the force on you was from inertia or gravitation. While Newton's Law of Universal Gravitation works well for ordinary gravitational fields, it is inaccurate when the gravitational intensity is high. Albert Einstein formulated the **theory of general relativity** in 1914 as a new way to explain gravity.

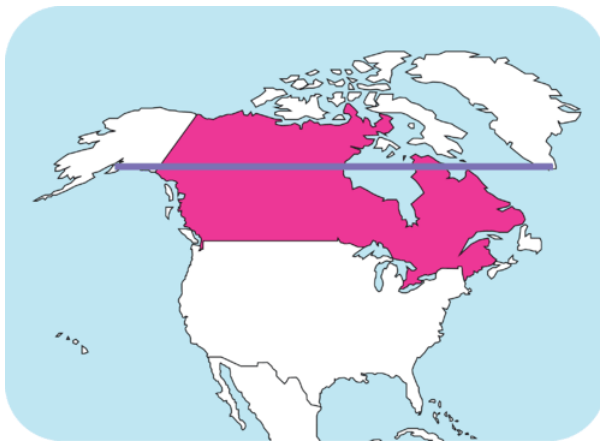
The classical explanation of gravity is that a force of attraction acts at a distance between two objects and the magnitude of the force is directly proportional to each of the masses and inversely proportional to the square of the distance between the objects. The objects move toward each other due to this force of attraction. Einstein's new concept of gravity states that matter (mass) causes the space around the matter to curve and also distorts time. A straight line through this curved space would also be curved in order to be a straight line.

Suppose we take a model of the earth in the shape of a globe and draw a straight line on the globe that travels from Kodiak Island, Alaska to the southern tip of Greenland. This straight line passes northward of Hudson's Bay, missing it entirely.



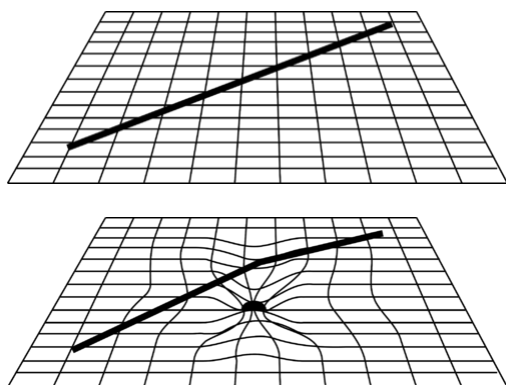
Now suppose we take a map of Canada that has been flattened to exist in two dimensions and once again, draw a straight line from Kodiak Island, Alaska to the southern tip off Greenland.

This time, the straight line cuts right through the middle of Hudson's Bay.



Why the difference? The actual space occupied by the earth is three dimensional and spherical. When that space is altered in order to fit it onto a two-dimensional sheet of paper, the actual geometry of the surface is altered. A straight line on a curved surface does not mean the same thing as a straight line on a flat surface. When an object travels through curved space, it must follow the curvature of the space in order to move in a straight line.

When there is no mass in a volume of space, the space is not curved. An object passing through such space would follow a straight line in our normal way of thinking of a straight line.



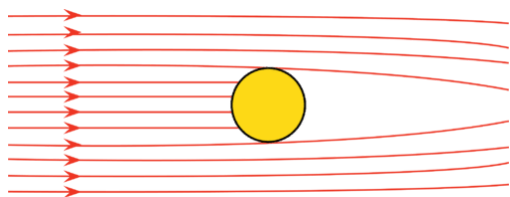
When a large mass is placed in the space, however, the space is curved due to the presence of the mass. In this case, an object passing through the space must follow the curvature of the space in order to follow a straight line. Thus the path of the object bends toward the mass. The change in the direction the object appears to be exactly the same as it would have been following Newton's law of gravity.

In the general theory of relativity, objects move toward each other not because of a force that acts at a distance but because they are following curved space. The mathematical expressions describing the properties of a gravitational field around a mass are given in a set of formulas called the *Einstein Field Equations*. These formulas are a highly complex system of partial differential equations, which are beyond the scope of our material. Under normal levels of gravitational field strength, however, the relativistic mathematics for gravity reduce to Newton's mathematics for gravity. When gravitational field strength is extremely high, however, the correct movement of objects can only be calculated with Einstein's relativistic gravity. Mass tells space how to curve and space tells mass how to move.

Experimental tests to garner support for the general theory of relativity were not easy to find. The first involved the orbit of the planet Mercury. The orbit of Mercury (the closest planet to the sun) exhibits perturbations and a precession that could not be fully explained by Newton's Law of Universal Gravitation. The motion of Mercury was in much greater agreement with the predictions from the equations of general relativity. The acceptance of the theory of general relativity increased greatly after it was shown to correctly predict the orbit of Mercury.

Both Newton's theory of universal gravity and the theory of general relativity predict that light can be deflected by gravity. The calculation of the amount of deflection predicted by Einstein's theory was approximately double that predicted by Newton's theory. The deflection of light by gravity was tested in 1919, five years after general relativity was proposed.

Two British groups took photographs of a region of the sky centered on the sun during the May 1919 total solar eclipse and compared the positions of the photographed stars with those of the same stars photographed from the same locations in July 1919 when the sun was far from that region of the sky.



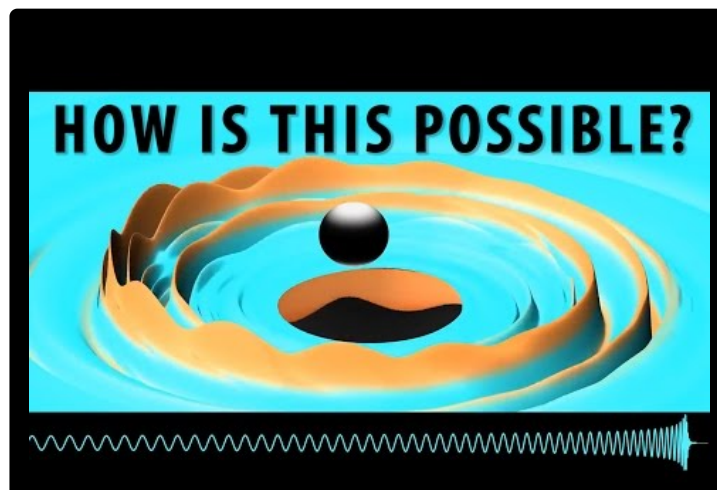
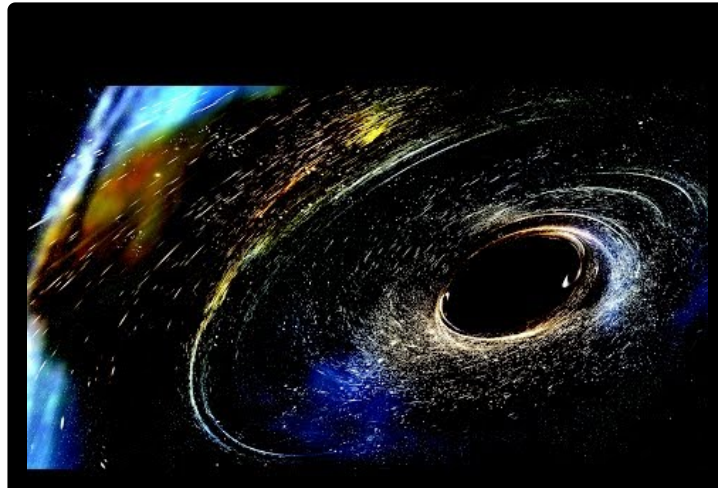
The results showed that light was deflected when the sun was present, and also that this deflection was consistent with general relativity but not with “Newtonian physics”. The subsequent publicity catapulted Einstein to world fame. (To date, he is the only scientist to ever have a ticker-tape parade in New York City.)

Gravitational Waves

Einstein first hypothesized the existence of gravitational waves in 1916. They were thought to be waves in the fabric of space-time, like ripples in a smooth surface of water. These waves were proposed to carry energy in the form of gravitational radiation, temporarily stretching and compressing matter as they pass through.

On February 11, 2016 (one hundred years after Einstein’s prediction), researchers from the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) announced the first detection of a gravity wave! The signal, a short, quarter-second blip of sound, is an auditory representation of the ripple felt by the two LIGO observatories on either side of the United States. It was caused by the merging of two black holes 1.3 billion light years away.

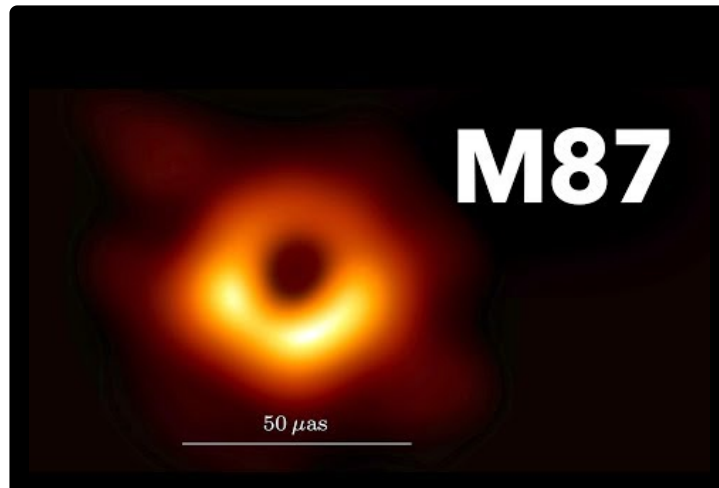
[Listen to the sound here!](#)



Other Predictions of the General Theory of Relativity

Einstein's general theory of relativity states that time is a fourth dimension adding to the three dimensions of space. Einstein called this four-dimensional geometry spacetime. The general theory of relativity also predicted light coming from a strong gravitational field would have its wavelength shifted toward longer wavelengths, called a red-shift. The theory also predicted that when gravity becomes great enough, it would produce objects called black holes. Black holes are objects whose gravity is so massive that light cannot escape from the surface at all. Since no light can escape, such objects would appear black. Both gravitational red-shift and black holes were considered possible in the Newtonian theory, but measurements correspond better with Einstein's theory.

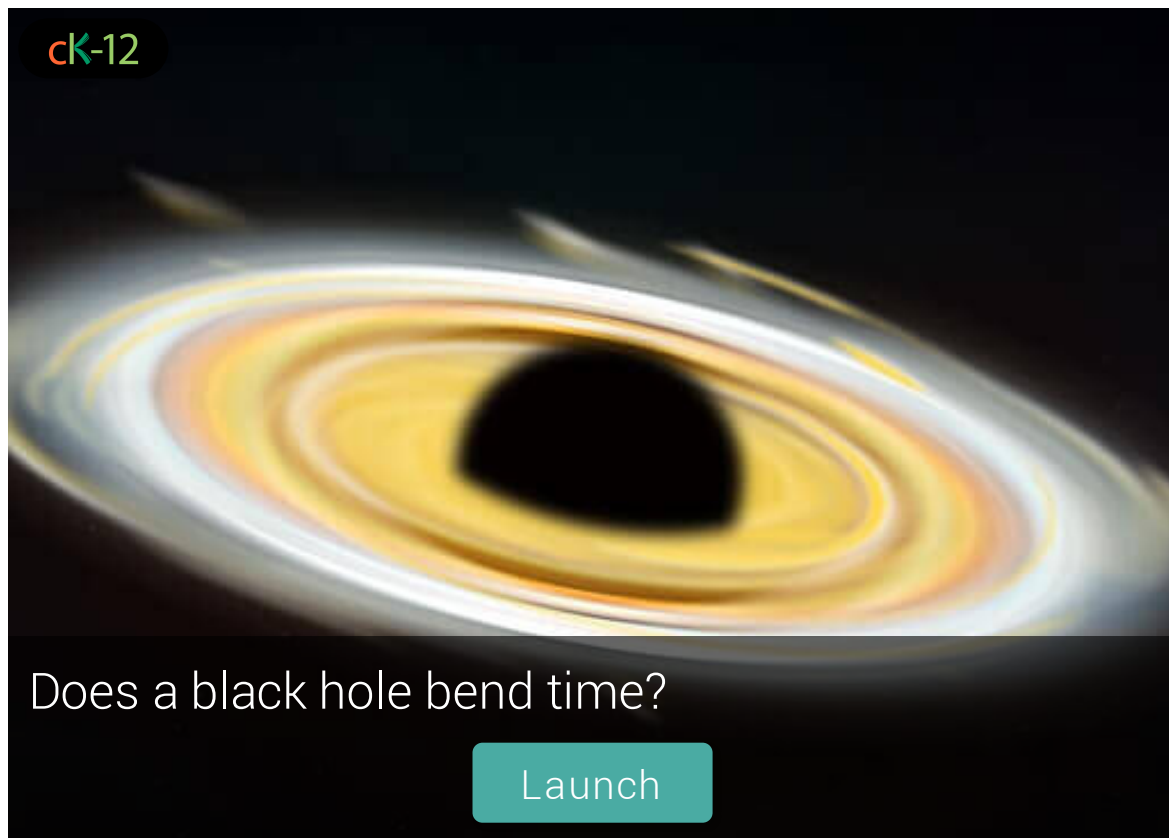
On April 10th, 2019, the Event Horizon Telescope (EHT) revealed it has successfully captured images that provide the first visual evidence of a supermassive black hole. To learn more, watch the video below:



There are also interesting effects having to do with the “curved time” predicted by the theory of relativity. This effect manifests itself by causing time to go slower near a massive object. The theory suggests that time on the top of a mountain runs faster than it does at sea level. Gravity's slowing down of time also affects the frequency of light waves and therefore their color. Light becomes bluer as it approaches a massive object and redder as it moves away. This effect was first observed in 1960 by Robert Pound and Glen Rebka, who shot gamma rays up to the top of a building and measured the change in their color as they got farther away from the Earth.



Launch the simulation below to further explore Black Holes. Explore what happens as you approach the event horizon, the area in which light can no longer escape. Try to observe the warping of spacetime that occurs near the event horizon that causes the clock to appear to run slower. Then, change the sliders to also observe how radio signals are stretched to longer wavelengths, resulting in lower frequencies:



<https://www.ck12.org/flx/show/interactive/user:ck12science/http://www.ck12.org/embed/#module=launcher&artifactID=1935125&nochrome=true?hash=50cd08986086bf2e3738f7243c86b955>

Further Reading

- Time Dilation
- Length Contraction

Summary

- Masses placed in space cause the space to be curved.
- Curved space causes masses moving in a straight line to follow a curved path.
- Curved space also caused time to run more slowly.

Review

1. The general theory of relativity was a new way of understanding
 - a. the speed of light.
 - b. gravity.

- c. mass.
 - d. force.
2. Gravity can bend the path of light.
- a. True
 - b. False
3. Strong gravitational fields can alter the rate of time passing.
- a. True
 - b. False
4. Under what circumstances will a light beam follow a curved path?
- a. when emitted from a moving source
 - b. when measured from an accelerating space ship
 - c. when measured in the presence of an extreme gravitational field
 - d. NEVER
5. If you are traveling toward the star Sirius at 1.5×10^8 m/s, what speed would you measure for the speed of light arriving at your ship from Sirius?
- a. 3.0×10^8 m/s
 - b. 1.5×10^8 m/s
 - c. 4.5×10^8 m/s
 - d. 0 m/s

Explore More

Use this resource to answer the questions that follow.



1. If you have two objects and one of them is moving and one is standing still, what experiment can you do to determine which object is moving?

2. If a person in a spaceship flies by a person on the earth and each person assumes that they are standing still and the other one is moving, which person is correct?
