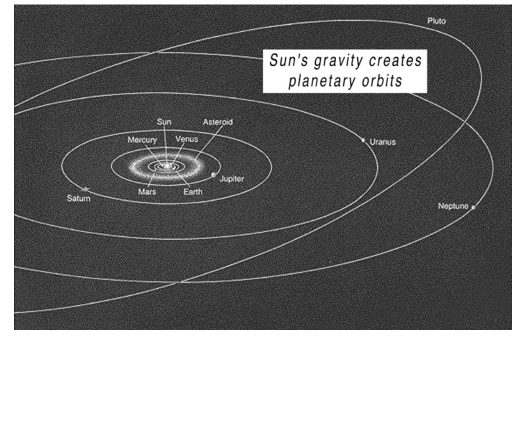
What Was Wrong With Gravity?

In Einstein's General Theory of Relativity (1916), space is transformed from the Newtonian idea of a vast emptiness with nothing but the force of gravity to rule the motion of matter through the universe, to an invisible fabric of spacetime that "grips" matter and directs its course.

Two Observations, One revolution



Newton's theory of gravity (1687) is as familiar to us as walking down a hill. As we put one foot in front of the other, the invisible force of gravity reaches out from the Earth and pulls each foot down to the ground. We feel the pull of the force and let our foot fall to the ground and we continue down the hill on our merry way. The same invisible force that keeps us Earth-bound keeps the planets in orbit around the Sun. According to Newton, the Sun's gravity reaches out across empty space and constantly pulls the planets toward it, preventing them from zooming out of our solar system.

This theory remained the strongest explanation for the planetary orbits and the falling motion of objects on Earth for more than two centuries. It was not until the early 20th century when Einstein began working on his theories of relativity that Newton's theory of gravity was seriously challenged.

In 1905 Einstein presented his Special Theory of Relativity. Central to this theory was his claim that the speed of light in a vacuum (299,792 km/sec) was the speed limit of all matter and energy in the universe. While matter could approach the speed of light and energy could travel at speeds approaching or equaling the speed of light, they could never surpass it.

With this principle in hand, Einstein turned his attention to Newton's theory of gravity. Einstein focused on two observations that challenged Newton's theory. The first related to the speed limit of light, and its implications for the speed limit of the force of gravity. The second related to the Equivalence Principle, an idea explored since the time of Galileo.

#1 - Instant Propagation Problem

Newton stated that the attractive force of gravity emanated from all matter, but he did not explain how it physically transmitted from one mass to another, nor how long this transmission took to occur. He simply inferred that the force of gravity traveled instantly across empty space, propagating from one mass to another.

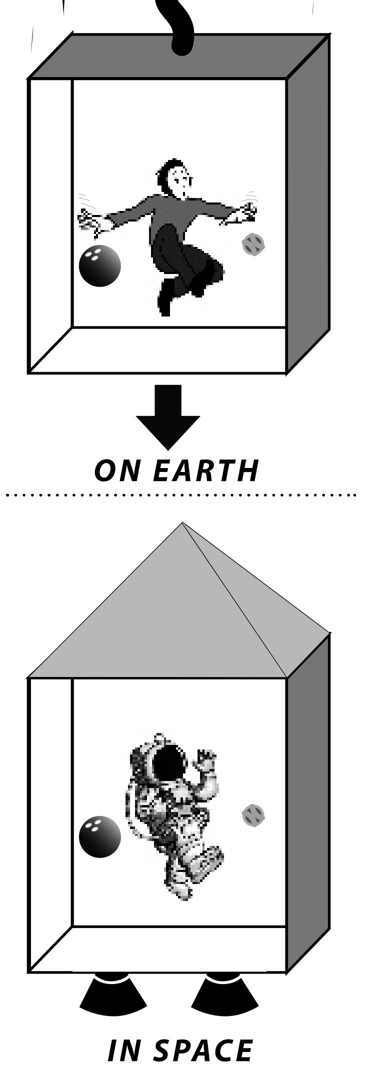
However, Einstein along with other scientists began to question this conclusion around the turn of the 20th century. In the 19th century, Maxwell had shown that electricity and magnetism propagated at the same finite rate in a vacuum -- 299,792 km/sec. Light was known to be a form of electromagnetism, because it too traveled at this rate. Einstein's theory of special relativity concluded that this rate was the speed limit for all energy and forces in the universe. No "information" could transmit across empty space faster than the speed of light -- not even the force of gravity.

Einstein's conclusion created a serious contradiction. Observations of planetary and lunar orbits showed that Newton's calculations were mostly correct. But, according to Einstein, there was no way that an object entering the solar system could "sense" the Sun's gravity instantly, no matter how fast the force could travel.

So who was correct? Was Einstein wrong in his conclusion that the force of gravity was restricted in speed like other forces? Was gravity something unique that followed its own laws of physics?

Einstein believed that he was not mistaken. Even though Newton's theory explained the planets' orbits to a great extent, it did not tell the whole story. Over the next ten years, Einstein worked to find the answer to the instant propagation problem.

#2 - The Equivalence Principle



In Einstein's search for a solution to this contradiction, his greatest breakthrough came when he realized that the Equivalence Principle revealed the underlying nature of space. This principle asserts that our experience of motion in a gravitational field is equivalent to our experience of motion in an accelerating frame of reference. If you jump off a chair on Earth, you fall to the ground at exactly the same rate as when you jump off a chair in an accelerating spaceship. In both places (or frames of reference), your motion is identical from your perspective.

Let's break this down a bit. In a spaceship accelerating upwards at 9.8 m/s^2, any object will "fall" to the floor at 9.8 m/s^2. On Earth, any object you drop will accelerate to the ground at 9.8 m/s^2. An observer could not tell the difference between gravity and an accelerating frame of reference, so the force of gravity could not be a conclusive explanation for the falling motion of objects in the universe.

In this new view, it is the curvature of spacetime that directs your motion. While gravity can still be considered a force, it can also be understood as a geometry of spacetime. When that geometry is curved, as it is around all masses, objects fall to the ground. The apparently empty space around us is not so impotent; it is the curvature of spacetime itself that keeps us on the ground.

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Equivalence Principle Demonstrations

Complete the following demonstrations to explore the Equivalence Principle as Einstein thought about it.

Do All Masses Fall At The Same Rate?

A: Dropping Balls

1. Collect several pairs of objects that are about the same size but different weights. For example, a regular golf ball and a plastic golf ball, a tennis ball and a baseball, an empty plastic soda bottle and a full plastic soda bottle.
2. Find a partner and take the objects to an empty space where you can drop them safely.
3. Stand on a stepladder or stable, sturdy chair to drop the objects from a high point.
4. Hold them out at shoulder height and drop each pair simultaneously.
5. Repeat several times with all objects.

* *Record your observations.*
* *Which objects hit the ground first? The heavier or the lighter? Why?*

B: Dropping a Bottle

1. Make a pencil-sized hole in the side of a plastic soda bottle, carefully using a pushpin and an exacto knife.
2. Cover the hole with your finger or duct tape and fill the bottle with water.
3. Hold the bottle as high above the ground as you can.
4. Uncover the hole and observe what happens to the water.
5. Release the bottle and let it fall to the ground. Observe what happened to the water as the bottle fell.

* *Record your observations.*
* *Why did the water stay in the bottle while it was falling?*

C: Swinging Pendulums

1. Find a place to hang and swing a paper cup. You can attach it to the top of a doorway, to the edge of a table, to a basketball backboard, or to a pipe.
2. Tie a length of fishing line to a paper cup and attach it to the doorway. Make the cup hang as low as possible without hitting the ground.
3. Tie a second cup and attach it. Make sure it is the exact same length.
4. Collect materials of different mass that you can put in each cup *(e.g., sand, popcorn, dirt, rocks, paper, peanuts)*
5. Fill each cup with materials of different masses, so that one cup is significantly heavier than the other.
6. Slowly swing both cups up into the starting position.
7. Release the cups simultaneously.
8. Observe which cup reaches the bottom of the arc first.
9. Repeat several times with different materials.

* *Record your observations.*
* *Which cup reaches the bottom of its arc first? The heavier or the lighter cup? Why?*

D: Accelerating Spaceship

1. Stand on a stepladder or stable, sturdy chair again, as in Demonstration A.
2. Take just one ball this time.
3. Hold it out at shoulder height and get ready to drop it. But hold on...
4. Before you drop it, imagine you are floating in a spaceship in outer space, far from any gravitational fields.
5. Imagine that the ball you are holding is actually floating next to you. Hold your palm out flat and imagine that the ball would float there if you took your hand away.

Equivalence Principle (cont.)

6. Now, do two things at the same time.
   a) Release the ball, and
   b) Accelerate your spaceship upwards at 9.8 m/s^2.
7. Repeat this several times until you can really imagine that the engines are accelerating you upwards at the same instant that you release the ball.

* *Record your imaginary observations.*
* *Why does the ball appear to "fall" in this imagined situation?*
* *What do you think the laws of physics are like in a spaceship accelerating at 9.8 m/s^2? Would it be harder to walk or play catch or climb stairs or jump than here on Earth?*

Summary -- From these demonstrations, you should see that all objects fall to the ground at the same rate in a vacuum, regardless of their mass. They accelerate at the same rate and hit the ground simultaneously. This is counter-intuitive because we assume that heavier objects fall faster since heavier objects hit the ground with more force. In addition, it should be apparent that in a spaceship accelerating at 9.8 m/s^2 the laws of physics would be the same as they are here on Earth. In fact, it would feel just like being on Earth.

THIS IS THE EQUIVALENCE PRINCIPLE.
GRAVITY IS ACCELERATION. ACCELERATION IS GRAVITY.

EINSTEIN'S "HAPPIEST THOUGHT"

"For an observer falling freely from the roof of a house, there exists - at least in his immediate surroundings - no gravitational field. Indeed, if the observer drops some [masses], then these remain to him in a state of rest, or uniform motion....

The observer, therefore, has the right to interpret his state as 'at rest' [even though he appears to be falling to the rest of us]."

-- From Einstein's "Morgan manuscript" in "Subtle is the Lord", Abraham Pais, p.178

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