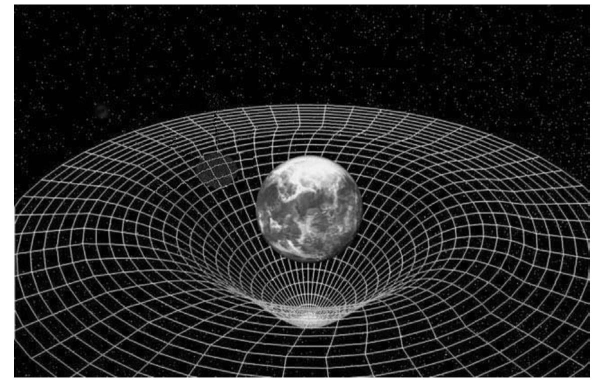
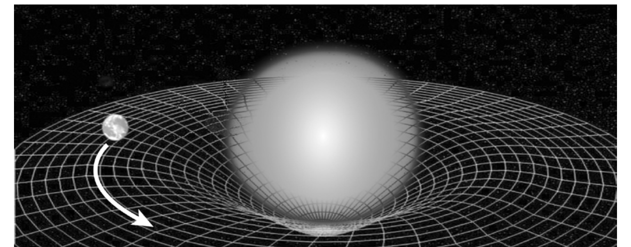
A New Understanding: Curved Spacetime



In 1916, Einstein presented the world a new understanding of the universe: his General Theory of Relativity. In this theory, space is not an empty void, but an invisible structure called "spacetime". Nor is space simply a three-dimensional grid through which matter and light and energy move. It is a four-dimensional structure whose shape is curved and twisted by the presence of matter.

What exactly is this "spacetime" that Einstein spoke of?
For many, "spacetime" sounds like a science fiction concept where explorers travel through time on the way to parallel universes to meet alien life forms. In some ways, it is a simpler idea than that. The term "spacetime" simply refers to a frame of reference in which the three dimensions of space (x, y, z) and the dimension of time are used to describe motion or action in that frame of reference.

Where spacetime gets interesting is when one considers that it is a frame of reference that is not always square. When a mass is present, such as a star or planet, the spacetime frame is deformed or curved by its presence. This means that the frame of reference, by which we measure the motion of things, is not a grid of straight lines and right angles but a grid that can be warped and curved. This idea contrasts directly with Newton's concept of a fixed, immovable, universal grid upon which all motion can be measured.



Take, for instance, the orbit of Mars around the Sun. From our perspective, it appears as though Mars is following a curved path through space. We think it is curved because we compare it with an invisible, fixed, square background.

However, we can also imagine that Mars is following a straight path through space. It is a "straight" path because it is following the shape of spacetime. It just so happens that space itself is curved due to the presence of the Sun.

How Does Curved Spacetime Explain Orbits?

Our solar system is filled with objects following orbital paths. Planets orbit the Sun. Moons orbit the planets. Satellites and the International Space Station orbit the Earth. When Newton looked up at the night sky in the 17th century, he observed these orbital motions and concluded that, in accordance with his laws of motion, there must be a force acting on these objects to keep them in orbit.

Why must there be a force? Because these objects were clearly moving in curved paths. According to Newton's law of inertia, the only way that an object would change direction from a straight path was if a force was acting on it. Since the planets and moons were constantly changing direction (an orbit is an infinite series of turns), there must be a force constantly acting on them. Newton's conclusion was that the force was "gravity" – an attractive force that emanated from each mass and pulled other masses in toward it.

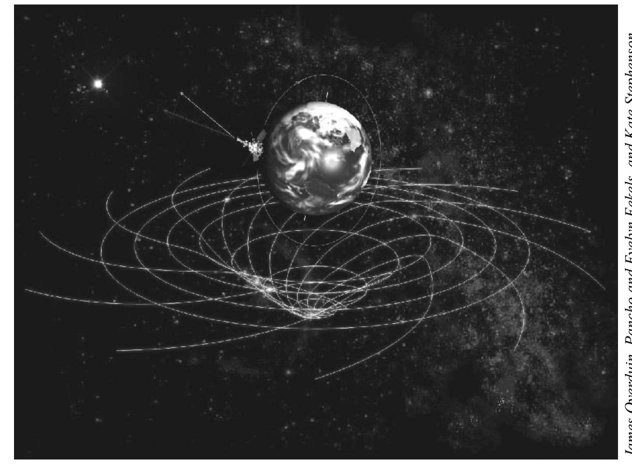
Einstein came to a different conclusion. From his perspective, the planets and moons in orbit in our solar system are not moving in curved paths. In fact, they are following straight lines through spacetime. It is spacetime that is curved, not the paths of the orbiting bodies. Since these bodies are not curving or turning, there is no force acting on them. No force is needed to explain these orbits; therefore, the attractive force of gravity does not exist. In fact, the orbiting masses are simply reacting to the shape of spacetime.

How could the Earth, which so clearly seems to follow a curved path around the Sun, be said to be following a straight path? First, look closer at what "straight" means – it describes the motion of an object that stays parallel to a line in its frame of reference. Second, imagine that the grid lines on our frame of reference are curved. Around the Sun, the frame of reference is circular because the mass of the Sun has warped spacetime around it. Finally, trace the path of the Earth around the Sun. Notice that its path, while appearing curved at first, is actually moving parallel to the circular spacetime grid around Earth. The Earth is following a straight path around the Sun.

This is how curved spacetime explains the orbital motion of all matter in the universe, from satellites to planets to binary stars to swirling galaxies, in addition to the Space Shuttle and the International Space Station. The presence of a mass has an ability to curve local spacetime. As matter moves near the central mass, it follows this curve of spacetime.

A Second Implication: Frame-Dragging

A few years after Einstein submitted his theory of curved spacetime, Austrian physicists Joseph Lense and Hans Thirring predicted that a mass could deform spacetime in a second way - through "frame-dragging" (1918). They proposed that the rotation of planets and stars or any rotating mass twists the spacetime frame near that mass. For example, not only is local spacetime curved near the Sun, it is twisted by the Sun's rotation.



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Lense and Thirring predicted that this effect would be extremely small, and become smaller farther from the rotating mass, but it would occur around every rotating mass, be it a planet, a star, a galaxy, or a person. As yet, it is unclear how this phenomenon is supposed to occur, but the mathematical equations conclude that if masses curve spacetime, then they also must twist spacetime.

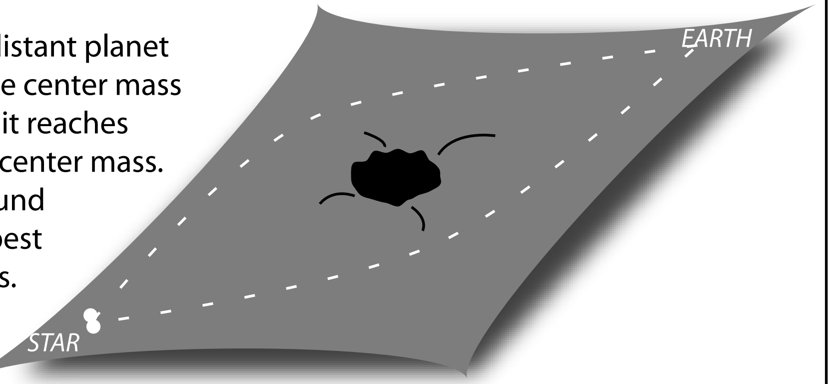
Models of Spacetime

Using a plastic frame and spandex sheet, you can create a simple model of curved spacetime. On this model, you can demonstrate several phenomena that are caused by the curvature of spacetime.

Materials
- * Spandex sheet, 6'x 6' -- *(order from fabric store or web site)*
- * PVC pipes and joints -- *(cut to build a 5'x 5'x 3' frame; complete instructions at http://einstein.stanford.edu/)*
- * Large weights -- *(bags of sand or water, iron/brass weight)*
- * Small and large balls -- *(superballs, steel/brass ball bearings, ping pong balls, golf balls, beach balls, etc.)*

A & B -- Satellite and Planetary Orbits

1. Place a heavy mass in the center of the sheet to create a sizable depression.
2. Pass out a small ball to each pair of students. Take turns to try out challenges.



Challenge A – You are sending a satellite to explore a distant planet behind a nearby planet. Stand on opposite sides of the center mass (the "near planet"). Roll the ball (your satellite) so that it reaches your partner (the "distant planet") without hitting the center mass.
Challenge B – You want to put a satellite into orbit around the "near planet". Work together and figure out how best to put your "satellite" into orbit around the center mass.

C & D -- Bending Starlight & Gravitational Lenses

1. Place a heavy mass in the center of the sheet to create a sizable depression. Remind students that electromagnetic waves (such as light) follow the curve of spacetime just like masses do.
2. Put students in groups of three. One person is a "star" emitting light in the form of a photon-ball. One person is an observer on Earth. The third person is the "marker".

Challenge C - Demonstrate how starlight bends around large masses. Roll a ball from the "star" on one side of the sheet to the "Earth" on the other side of the sheet. The star and Earth should be directly opposite each other. The third person spots the point where the "photon-ball" turns towards the Earth. Once, she spots that point, she stands at the end of line coming from the Earth through the "turning point". She is now the "apparent star."
Challenge D – Demonstrate a gravitational lens. Have the "star" student roll two "photon-balls" around opposite sides of the central mass. Keep trying until both balls reach the "Earth" at the same time. Two students mark the "turning points" and stand in line with each point and the Earth. These students are two "apparent stars" created from the light of a single star.

* Stars emit light in all directions, so starlight does not just go around one side of a central mass. If the star and the central mass are aligned properly, the star will appear on multiple sides of the central mass. It may appear as if there are several stars around the central mass. In fact, these stars are all part of the light coming from a single star.

E -- Bigger Objects = Greater Gravity?

Which causes more curvature of spacetime (stronger gravity) -- the Earth or a white dwarf star?

Even though they are the same size, the white dwarf is much more massive and creates a greater curvature of spacetime. Demonstrate the distinction with a whiffle ball and a baseball on the spandex sheet. The whiffle ball creates a much smaller depression or curve of spacetime than the baseball creates.
Why? Because the baseball is more massive. In this case, mass matters, not size.

	Earth	White dwarf (avg.)
Size	12,756 km	~ 13,000 km
Mass	6×10^{24} kg	~ $1,100,000 \times 10^{24}$ kg

Models of Spacetime (cont.)

Questions

A & B

1. *What are the three key variables you must control when directing a satellite to where you want it to go?*
2. *Why is it impossible for you to put your "satellite" into perpetual orbit in this model, even though we do it in space all the time?*

C & D

3. *Where does the star appear to be to the Earth-based observer?*
4. *Why is one star called an "apparent star"?*
5. *This phenomenon is called a "gravitational lens". What does it have to do with gravity?*
6. *How is this phenomenon similar to what a lens does to light?*

E

7. *What characteristic determines the amount of spacetime curvature or gravitational strength -- volume or mass?*
8. *What about the Sun and a neutron star? The Sun is about 100,000 times larger, but the neutron star has a little more mass. The Sun covers much more space; does this cause more curvature?*
9. *Do more dense objects always create more curvature than less dense objects?*

Answers -- *#1 -- Initial speed, initial direction, distance of orbit from planet; #2 -- Friction between ball and sheet reduces speed causing ball to lose momentum; no friction in space so satellite's momentum remains constant; #3 -- At the turning point, to the side of the central mass; #4 -- The star appears to be to the side of the central mass, but is actually behind the central mass; #5 -- The curvature of spacetime, which bends the starlight, is referred to as gravity; #6 -- Just like a lens, the curvature of spacetime around the central mass bends incoming light and focuses it to a common point; #7 -- Mass determines curvature or gravitational strength; #8 -- Even though the Sun covers more space, the more massive object always creates more curvature or gravity; #9 -- No. A denser object may not have as much mass as a less dense object. Compare a steel ship and a quarter. The ship is less dense (it floats), but has more overall mass.*

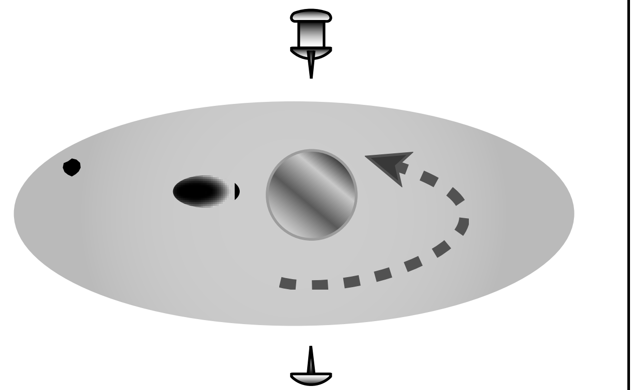
Demonstration of "Frame-Dragging"

The purpose of this activity is to demonstrate how the Earth twists the local spacetime frame, but does not affect a distant spacetime frame.

Materials: Paper plate, honey, superball, food coloring, thumbtack, pushpin, peppercorn

Procedure:

1. Poke a tack through the center of the plate pointing upwards.
2. Pour a layer of honey on the plate.
3. Place the ball firmly on the tack.
4. Place a peppercorn in the honey near the edge of the plate.
5. Squeeze a drop of food coloring in the honey around the ball.
5. Twist the superball as fast as you can.
6. Observe the effects of the twisting ball on the honey.



Questions:

1. *How does the honey react differently near the ball than far from the ball?*
2. *What do the parts of the model represent? The ball? The honey? The peppercorns? The food coloring?*
3. *What causes the "dragging" in the model?*

Summary:

The ball represents the Earth, the honey represents spacetime, and the peppercorn represents a distant mass (stars, planets, etc.) in spacetime. The food coloring is used to highlight the honey's motion, and does not represent an astronomical object. The rotation of the Earth does twist the spacetime frame like the ball twists the honey, although it is not caused by "friction" between the Earth and local spacetime. The theory of general relativity states that spacetime and masses have a mysterious mutual "grip" on each other.