ANOMALIES & TENSIONS IN COSMOLOGY · COSMOVERSE

CosmoVerse Adventures

Geometric Gravity

cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by the European Union

The classroom

Introduction: Newton's gravity

Teacher :

(Taking a bite of the apple) Good morning, young explorers! Are you ready for another CosmoVerse adventure?

Student 1 :

Always, sir! What's the topic today?

Teacher :

Well, let me give you a hint. The topic today was first introduced by a scientist who had a revelation while watching falling apples. Can any of you guess who this scientist was and what he discovered?

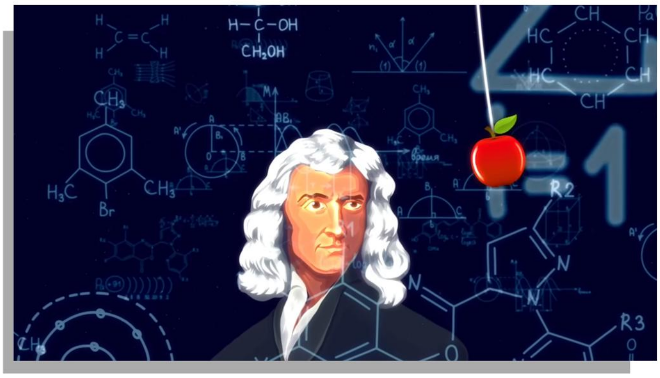


Figure 1: Artistic representation of Sir Isaac Newton. Image credit to klonusk.

Student 2 :

It was Sir Isaac Newton! He discovered gravity.

Teacher :

Excellent, that's right! We are going to talk about gravity today. But before that, let's watch this video.

(The teacher plays ***a video*** *of a bowling ball and a big feather falling down in a vacuum room.)*

Video 1: This snippet is taken from "Human Universe" documentary by BBC.

Teacher :

Before it starts, can any of you predict which will fall first?

Student 3 :

It makes sense that the bowling ball would fall first because it's heavier.

Teacher :

Let's watch and observe.

(Students watch in amazement as both the feather and the bowling ball fall at the same time.)

Student 3 :

Wow, they fell at exactly the same time!

Teacher :

Correct! In a vacuum, there's no air resistance. But the question is, why do the feather and the bowling ball fall down? Newton would say there's a force pulling them down, which is...?

Student 2 :

Gravity?

Teacher :

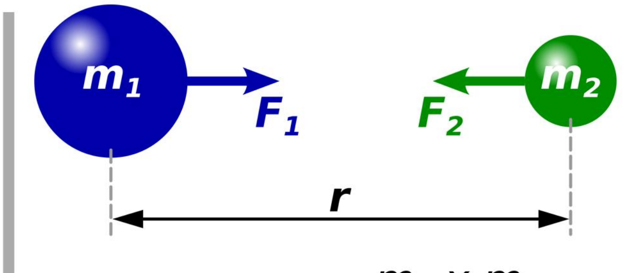
Exactly! Newton explained that every mass attracts every other mass. The strength of this force varies based on the mass of the objects and the distance between them. Everything happens just as Newton said, the earth orbits the sun, the moon orbits the Earth, and the universe itself works according to Newton's gravity. (See figure 2).

Student 3 :

But the distance between the Sun and the Earth is about 150 million kilometres, will there be a force for such a distance?

Teacher :

Brilliant question, and that’s the exact question that scientists started to ask, how does this force of gravity work over vast distances like between the Earth and the Sun? Here enters a young clerk who worked in a Swiss patent office, Albert Einstein. He had a revolutionary perspective on gravity, inspired by a simple observation.



$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

Figure 2: This diagram describes the mechanisms of Newton's law of universal gravitation. The force is proportional to the product of the two masses and inversely proportional to the square of the distance (r) between the point masses. Image credit to Chris H. Hardy.

Student 1 :

Was it another falling apple?

Teacher :

(Chuckles) Not quite. He was watching a man cleaning the windows of a building and wondered what would happen if that person fell. While it may seem strange to us to hear this, Einstein describes it as 'the happiest thought in my life'. This thought led him to one of the most ground-breaking ideas in physics.

Figure 3: Einstein’s theory of gravity vs Newton’s theory of gravity. Image credit to klonusk.

Student 4 :

A falling man? That wouldn't have a happy ending.

Teacher :

True, but Einstein thought about it differently. Instead of focusing on the impact, he imagined what the window washer would experience while he was falling. Now, put yourself in that window washer's shoes. What do you think you would feel as you were falling?

Figure 4: Einstein's happiest thought experiment of a falling man that led him to his theory of general relativity. Image credit to klonusk.

Student 2 :

Fear? And the wind rushing past? And maybe gravity would be pulling me down!

Teacher :

Since you're falling, gravity would be the only force acting on you. No ground pushing up against your feet, no chair supporting you, you would feel no weight. With no wind resistance, you would be in free fall.

Student 3 :

Oh, just like the bowling ball and the feather from the video! They're both in free fall too, right?

Teacher :

Spot on! In free fall, everything feels weightless. Einstein realized that the sensation of falling from a building would be indistinguishable from floating in deep space. But to fully grasp this, we need to venture beyond our classroom.

Student 1 :

Are we going on another adventure with Quark?

Teacher :

Exactly! Let's invite our cosmic friend, Quark, to take us aboard the Spaceship of Imagination, and explore this fascinating concept further!

Spaceship of Imagination

The perception of Gravity

Quark :

Welcome aboard, young explorers! Are you ready for another cosmic adventure?

Student 1 :

Always! What's the plan today, Quark?

Quark :

Today, we're going to experience gravity in a way you've never felt before. Strap in!"

(The students hurriedly find their seats, and the spaceship begins to ascend. As they reach space, the students start to float inside the spaceship.)

Student 2 :

This is incredible! We are floating, it's like swimming with no water around!"

Quark :

That's because our spaceship is coasting along at a constant velocity so you feel no force and no weight. Remember Newton's first law of motion?

Student 3 :

Yes, an object is at rest or moving at a constant speed in a straight line, it will remain at rest or keep moving in a straight line at constant speed unless it is acted upon by a force.

Quark :

Correct! Right now, you are a perfect example of an inertial observer. all the- objects here are stationary relevant to you. You are not accelerating, not in a gravitational field, and all the laws of physics apply just as you'd expect.

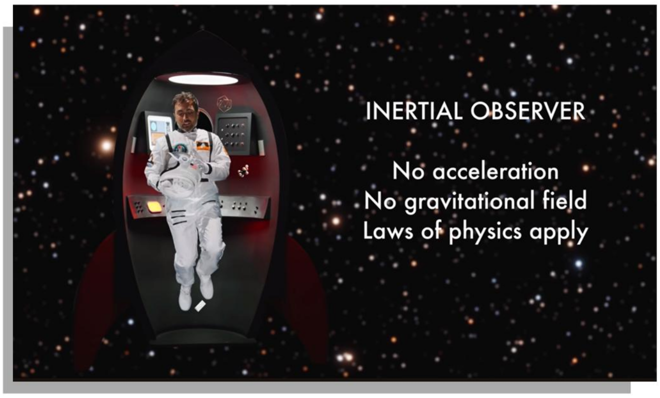


Figure 5: Inertial Observer is a hypothetical observer who is not accelerated with respect to an inertial system. Image credit to Veritasium.

Student 4 :

So, it means that there is no experiment, we could do to distinguish our initial reference frame from any other.

Quark :

Spot on! Now, let me close the windows for a moment.

(The spaceship started to fall down towards Earth)

Quark :

do you feel any difference now?

Student 4 :

I still feel the same, floating around.

Quark :

Interesting, isn't it? But let me open the windows.

Student 1 :

We're headed straight for Earth! But why don't I feel that?

Quark :

We're in a free fall. The spaceship, including us, is descending at the same rate. No force is working against us, hence, no sensation.

Student 4 :

Ah, just like the window washer in Einstein's thought experiment.

Quark :

Precisely! The sensation is identical, whether you're floating in deep space or plummeting towards Earth. It's all relative.

Student 2 :

It really is about perspective and frames of reference.

Quark :

Now let's add another layer to this.

(Quark closes the windows again and activates the motor engine of the spaceship and starts to accelerate upwards at 9.8 m/s^2)

Student 3 :

Whoa! I feel heavy, like I'm being pushed to the floor. Have we landed on Earth?

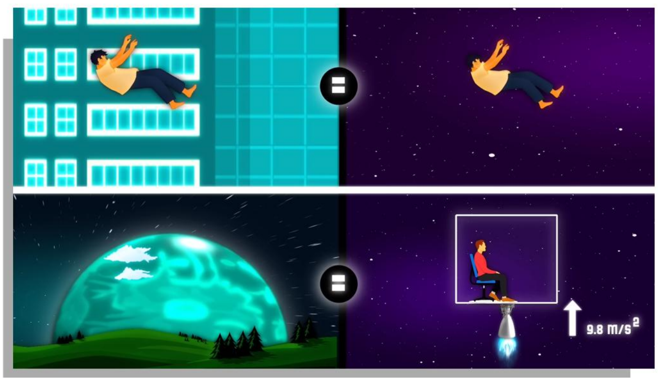


Figure 6: free fall on earth = Free movement in space. Gravity on earth = 9.8 m/s^2 acceleration in space; that is, acceleration causes gravity. Image credit to klonusk.

Quark :

No! we are now accelerating upwards at 9.8 m/s^2 which is 1G, the gravitational force for Earth.

Student 2 :

Oh, that's why it feels like we are on Earth. Again, I can't tell the difference.

Quark :

Exactly, so we learned that (Free fall on earth = Free movement in space) and (Gravity on Earth = 9.8 m/s^2 acceleration in space) and this is called Einstein's equivalence principle. Let's stop the engine so we can float again. Now, I will push this ball towards the centre, observe its path.

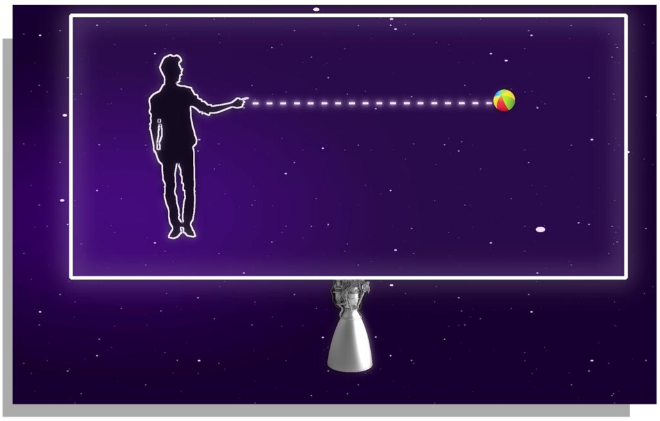


Figure 7: In a free fall, if you throw a ball, it will go in a straight line. Image credit to klonusk.

Student 2 :

It is moving in a straight line.

Quark :

Now let's switch on our motor engine and accelerate upwards at 9.8m/s^2 and throw the ball again.

Student 4 :

Now, the ball goes down in a curved path and hit the floor behaving as it would on Earth!

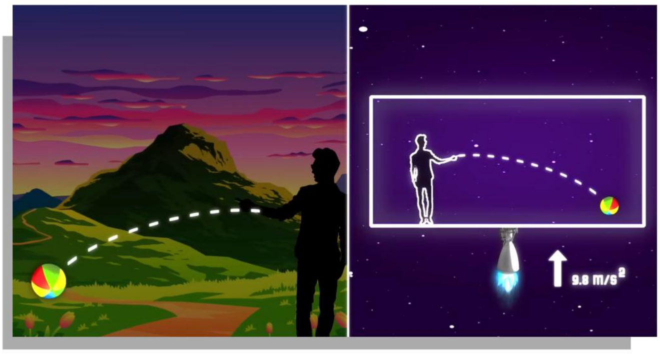


Figure 8: Throwing a ball in an accelerated spaceship with 9.8 m/s^2 = Throwing a ball on Earth. Image credit to klonusk.

Quark :

Exactly! But what if this ball was a beam of light? Will the light bend? Einstein said yes.

Student 2 :

But light always takes the shortest path between two points, right?

Quark :

Correct, Einstein postulated that the shortest path isn't always a straight line. Think about Earth's surface. The shortest distance between two points is a curve, not a straight line because of the curvature of Earth's surface.

Student 1 :

Like flight paths on Earth!

Quark :

Bingo! These paths are known as 'geodesics.' Another example, if we go straight from one place on Earth to the North Pole. As far as we are concerned, we are going straight line, but to an outside observer, we appear to be taking a curved path.

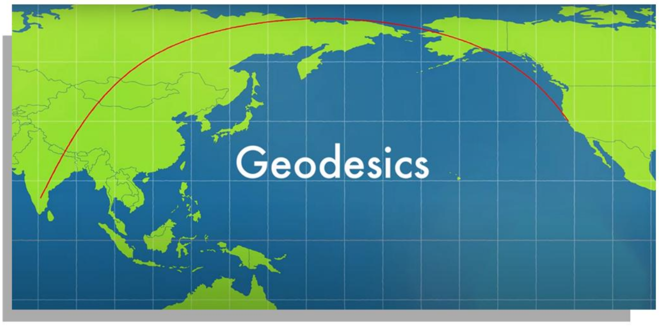


Figure 9: Geodesics can be thought of as the "straightest possible" paths in a given space. Earth is round, so the shortest path follows a curve over the surface. Airplanes follow these paths to minimize flight distance. Image credit to Veritasium.

Student 4 :

So, Einstein's idea was that the presence of mass and energy somehow causes space itself to curve?

Quark :

Exactly, leading to his ground-breaking general theory of relativity that he published in 1915.

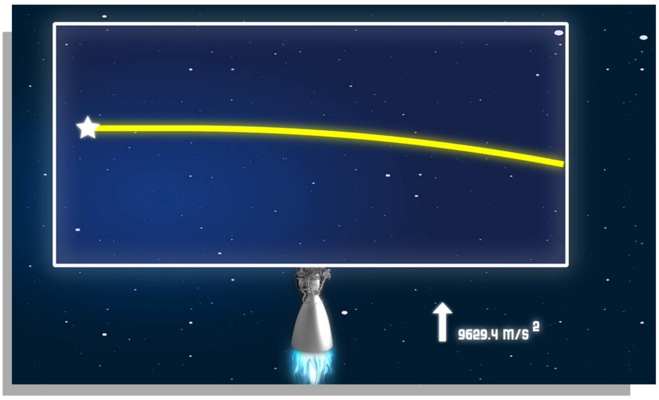


Figure 10: The greater the gravitational acceleration, the stronger the curvature of space-time around it, resulting in a more pronounced bending of light. Image credit to klonusk

Student 1 :

Yes, but even if it bends, we can't see it at this acceleration speed of only 9.8m/s^2.

Quark :

That's right, so let's increase our acceleration speed so you can observe the light bending.

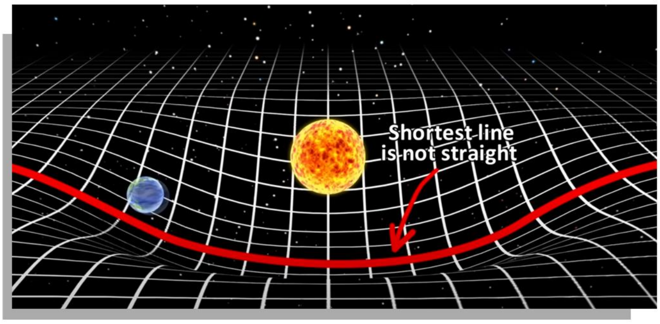


Figure 11: A visualization of the curvature of space-time around massive objects, where the red line represents the geodesic—a path demonstrating that the shortest distance between two points is not a straight line but a curve shaped by gravity. Image credit to Arvin Ash.

Student 3 :

Wow, Einstein was correct! But how was this proven at his time?

Quark :

A fantastic question! To understand it best, let's meet the genius behind the theory. Off we go to meet Professor Albert Einstein.

Meet a scientist

The Theory of General and Special Relativity

Quark :

Students, meet someone who changed our understanding of the universe. The legendary Albert Einstein!

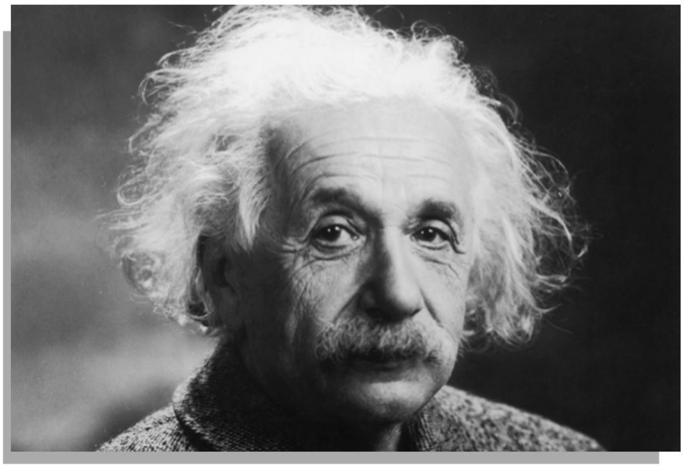


Figure 12: Albert Einstein. Image credit: Library of Congress.

Einstein :

Guten Tag, young explorers! Delighted to share a cosmic moment with you.

Student 1 :

It's an honor, sir! Quark told us about your groundbreaking work on relativity and how space itself is curved. But we're curious, how was such a radical idea proven during your time?

Einstein :

Ah, a curious mind! For my theory to gain acceptance, it had to make a prediction that was testable and distinct from other explanations. The key was in the peculiar orbit of Mercury.

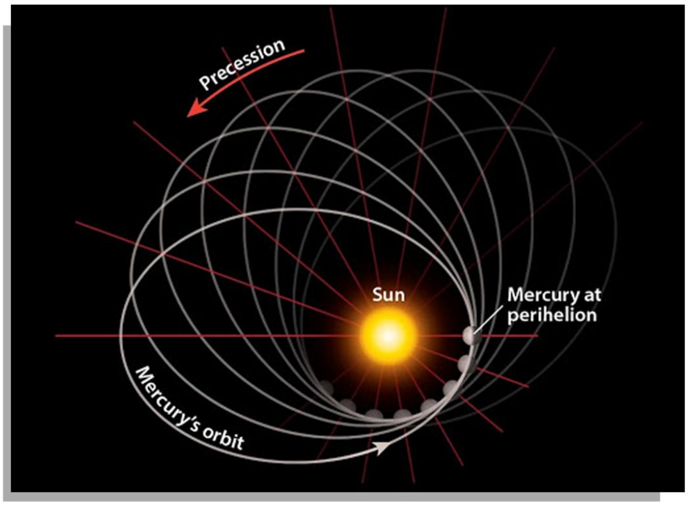


Figure 13: Artist's exaggerated impression of Mercury's shifting of orbit. This considered the first triumph of Albert Einstein's 1915 General Theory of Relativity.

Student 2 :

Oh! Is that the planet that doesn't orbit the Sun in a closed ellipse?

Einstein :

Precisely! Mercury's orbit has a precession, meaning its elliptical orbit never closes perfectly. Instead, the farthest point of its orbit from the Sun advances slightly with each revolution. This anomaly puzzled scientists, as Newton's equations couldn't explain it. But when I applied my theory of curved space, it predicted Mercury's exact observed precession!

Student 3 :

That must've been such a "Eureka!" moment for you!

Einstein :

Indeed! To imagine, for a moment, I was the only soul who understood this cosmic dance. But, while Mercury was a triumph, many of my peers remained skeptical.

Student 1 :

So, how did you convince them?

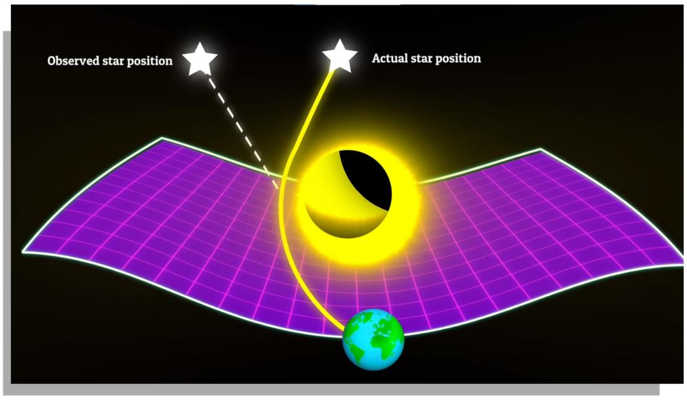


Figure 14: A demonstration of gravitational lensing, where light from a star is bent by the sun's gravity, causing the star to appear at a different position in the sky as viewed from Earth. The effect illustrates the curvature of space-time predicted by general relativity. Image credit to klonusk.

Einstein :

The most conclusive evidence came during a solar eclipse in 1919 nearly four years after I published my theory. An English astronomer, Arthur Eddington, led a team to photograph stars near the Sun during this eclipse. My theory predicted that starlight passing close to the Sun would bend due to the curvature of space created by the Sun's gravity.

Quark :

And if Einstein was correct, the observed position of these stars would differ from their expected positions without the Sun's influence.

Einstein :

Spot on, Quark! When Eddington's team analyzed the photos, the starlight had bent exactly as I had predicted. This experiment was a solid confirmation of my theory, and it changed the course of physics forever.

Student 1 :

I get space curvature, but we often refer to the term "space-time," not just space. How does time enter into the picture?

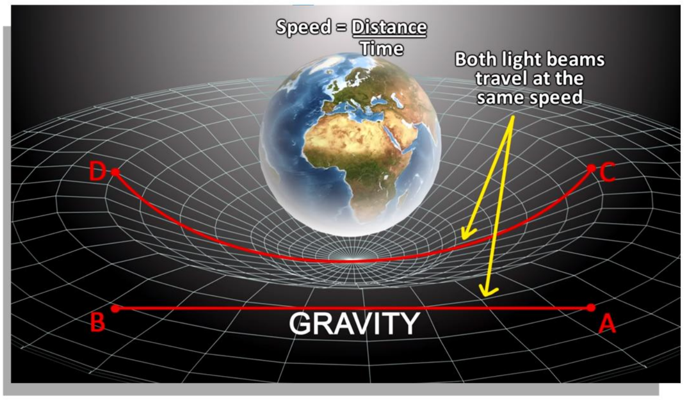


Figure 15: As the distance traveled by light DC which is under the influence of gravity is greater than light BA which isn't. To keep the speed of light constant, time itself must pass slower in the gravitational field relative to the time in empty space. Image credit to Arvin Ash.

Einstein :

Excellent query. To answer that, we must step back a bit and visit my first theory: special relativity published in 1905. At its core, this theory presumes that light's speed remains constant, regardless of one's perspective or reference frame. So, whether you're accelerating or resting, light will always travel at the same speed.

Student 3 :

But, Professor Einstein, how does that relate to gravity and time?

Einstein :

Let's consider this: Speed equals distance over time, represented as S= D/T. Now, in the presence of a gravitational field, light's path becomes longer due to the curvature of space. If we want the speed of light to remain unchanged, something must give—and that something is time. Time passes slower in a gravitational field relative to empty space.

Student 1 :

So, are you saying that time bends with gravity just like space does?

Einstein :

Precisely! The curvature of space near a gravitational field affects time, ensuring the speed of light remains constant in both environments. This interwoven fabric is what we call space-time.

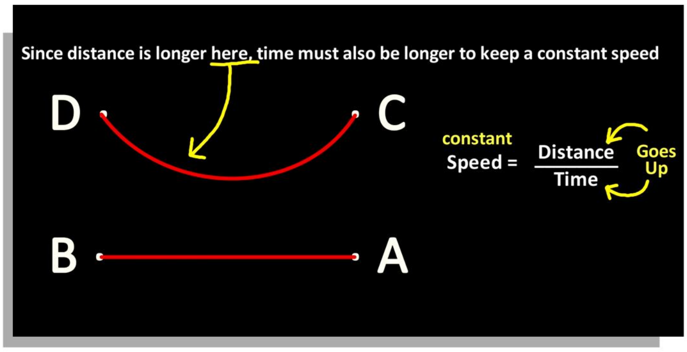


Figure 16: Since distance is longer between DC, time must also be longer to keep a constant speed. Image credit to Arvin Ash.

Quark :

To put it in context, clocks on Earth run slightly slower than those on the International Space Station. We've verified this effect through various experiments. It's even crucial for the GPS satellites' synchronization with Earth's clocks. Without this adjustment, your GPS apps would provide incorrect locations.

Student 4 :

Oh! This reminds me of the movie "Interstellar." There was a planet near a black hole where an hour on the planet was equivalent to seven years outside its gravitational influence. Was that based on your theories?

Einstein :

I haven't watched the movie but it seems like "Interstellar" movie did a remarkable job illustrating the effects of time dilation due to intense gravitational fields.

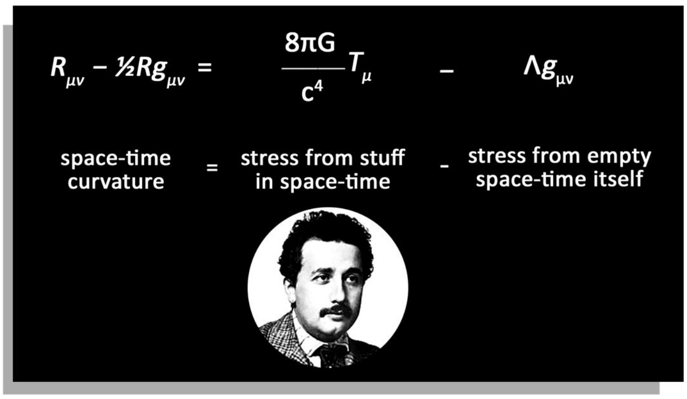


Figure 17: Einstein's field equations of general relativity, describing how matter and energy (stress from stuff in space-time) plus the cosmological constant (stress from empty space-time itself) dictate the curvature of space-time. Image credit to Arvin Ash.

Quark :

It seems our cosmic journey has more mysteries awaiting. Thank you, Professor Einstein, for enlightening us today.

Einstein :

The pleasure is mine. Always question, always wonder. The universe is full of enigmas waiting to be uncovered.

Action Lab

Demo 1: Free Fall Water Bottle

Objective :

To demonstrate the effects of free fall on objects and understand Einstein's theory that in free fall, objects no longer "feel" gravity in the same way.

Preparation Time : 5 minutes

Activity Time : 5 minutes

Materials Needed :

- A plastic bottle with a tight-fitting cap
- A pin or small nail to make holes in the bottle
- Water to fill the bottle
- Plastic sheet to contain the dripping water

Demonstration and Discussion :

Figure 18: holds up a bottle filled with water, with multiple holes from which water is spraying out. Image credit to giftofcuriosity,com

Teacher :

Alright students, let's put our knowledge to the test! We've learned quite a bit about free fall and how objects behave under the influence of gravity. Let's see Einstein's theory in action.

(He holds up a bottle filled with water, with multiple holes from which water is spraying out.)

Teacher :

As you can see, gravity is pulling the water out of the holes in this bottle. But Einstein's theory suggests that when in free fall, objects no longer "feel" gravity in the same way.

Student 2 :

So, if you drop it, the water will stop spraying out because it's in free fall?

Teacher :

Precisely! Ready to see it? Give me a count down from three.

Students :

Three, two, one...

(He drops the bottle, and as predicted, the water stops spraying out while the bottle is in free fall.)

Student 3 :

Wow! That was amazing!

Student 4 :

So, the water inside the bottle was in a state similar to weightlessness when it was falling?

Teacher :

Exactly. This is the essence of Einstein's understanding of gravity.

Action Lab

Demo 2: Space-time Rubber Sheet Gravity

Objective :

To visualize the concept of curved space-time as proposed by Einstein's theory of general relativity and understand how massive objects affect the space around them.

Preparation Time : 10 minutes

Activity Time : 15 minutes

Materials Needed :

- A large, stretchable rubber sheet or spandex fabric
- A frame or stand to stretch and secure the sheet (optional)
- A heavy ball (e.g., a metal or rubber ball)
- Smaller balls (e.g., marbles or ping pong balls)

Demonstration and Discussion :

Figure 19: A small sphere is pushed into orbit around the central mass. Image credit: NASA/JPL-Caltech **| + Expand image**

Teacher :

Now, let's understand the difference between Newton's gravity and Einstein's gravity. Newton envisioned a fixed space and time, where gravity was a mysterious force that acted between objects, even if they weren't touching. In this model, gravity operated within the realms of fixed space and time without affecting it.

Student 2 :

Yes, Einstein proposed that gravity isn't just a force between objects. Instead, it emerges from the interaction between space and massive objects.

Teacher :

Excellent! To put it succinctly, as John Wheeler later summarized the theory into 12 words: "Space-time tells matter how to move; matter tells space-time how to curve."

Student 1 :

So, the orbits of planets are determined by how space curves around them?

Teacher :

Correct! Let's brings out a rubber sheet and stretch it out. This is how the space would look like if we removed all masses and energy. Now let's see what will happen when I place a heavy ball in the center,

Student 4 :

It is causing a dip in the sheet.

Teacher :

Precisely. This heavy ball represents a celestial body, like the Sun. Its massive presence curves space. Now, roll these smaller balls around the central one.

Student 3 :

Wow, the smaller balls seem to orbit the central one, emulating planets in the curved space carved out by a sun.

Teacher :

Precisely! The smaller ball would follow the curve created by the heavier object. But remember, this analogy is in a 2D plane, just for visualization. The actual interaction happens in three dimensions. The real universe isn't a flat sheet; it's a vast expanse in every direction.

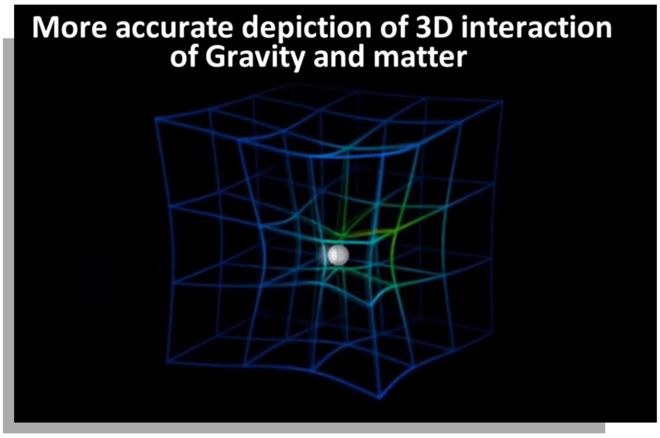


Figure 20: More accurate depiction of 3D interaction of Gravity and matter. Source: lucasvb.tumblr.com

Student 3 :

Thank you! These two demonstrations helped me to link theory to practice.

Teacher :

Brilliant! Today in our CosmoVerse adventure, we've seen that gravity is not just a force acting mysteriously at a distance but a curvature of the very fabric of the universe—space-time. We witnessed the genius of Einstein's vision. As we return to our daily lives, let's carry forward the sense of wonder and curiosity that has guided our exploration today, ever mindful of the profound mysteries of the cosmos that await our discovery.

Cosmic Library

Videos :

Why Gravity is NOT a Force
General Relativity Explained simply & visually
If light has no mass, why is it affected by gravity? General Relativity Theory
Einstein's Special Relativity Theory | Does Time really Slow down
Brian Greene Explains That Whole General Relativity Thing
How Does Gravity Affect Light?
Base for Special Relativity theory | Why is the speed of light constant
Special Relativity: Crash Course Physics #42
Brian Cox visits the world's biggest vacuum | Human Universe - BBC
Gravity Visualized

Interactive :

Modeling the Orbits of Planets
General Relativity explained like you've never seen before
A toolkit for teaching general relativity: II. Geodesics
Space-time concept
Relativity Simulator
Special Relativity: Time dilation

Websites & Articles :

Einstein Online
General Relativity
The Space Doctor's Big Idea

Documentaries :

What Inside Albert Einstein Mind The Theory of General Relativity Documentary
General Relativity, National Geographic
Einstein's Big Idea, PBS NOVA
Einstein's Universe: Understand Theory of General Relativity

Quiz :

General Theory of Relativity
General Relativity Theory of Gravitation
Relativity flash cards quiz

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Relativity 101

Glossary

Cosmological Constant: A term added by Einstein to his general theory of relativity to allow for a stationary universe, now understood as related to dark energy.

Equivalence Principle: A principle in general relativity stating that the gravitational force as experienced locally while standing on a massive body (like Earth) is the same as the pseudo-force experienced by an observer in an accelerated frame of reference.

Free Fall: The motion of a body where gravity is the only force acting upon it.

General Theory of Relativity: A theory of gravitation developed by Albert Einstein, which describes gravity not as a force, but as a consequence of the curvature of spacetime caused by the uneven distribution of mass.

Geodesics: The shortest path between two points in a curved space or spacetime.

Gravitational Field: The region around a mass where other masses experience a force of gravitational attraction.

Gravitational Lensing: A phenomenon where light from a distant object is bent around a massive object between the source and the observer, much like a lens.

Inertial Observer: An observer who is not accelerating and observes the laws of physics to behave in a standard, predictable way.

Light Bending: The phenomenon where light rays passing near a massive object are bent due to the curvature of space-time, predicted by Einstein's theory of general relativity.

Newton's Law of Universal Gravitation: A theory by Isaac Newton stating that every mass attracts every other mass with a force proportional to the product of their masses and inversely proportional to the square of the distance between them.

Precession of Mercury: The gradual shift in the orbit of Mercury, as predicted by general relativity, providing early evidence for the theory.

Quantum Mechanics: A fundamental theory in physics that provides a description of the physical properties of nature at the scale of atoms and subatomic particles.

Space-time: A four-dimensional continuum combining the dimensions of space and time. According to the theory of relativity, the presence of mass and energy "warps" space-time, and this curvature is what we perceive as gravity.

Speed of Light: A constant speed at which light travels in a vacuum, approximately 299,792,458 meters per second.

Time Dilation: A difference in the elapsed time as measured by two observers, due to a relative velocity between them or a difference in gravitational potential between their locations.

Wormhole: A hypothetical bridge or tunnel in spacetime that could connect extremely distant points in the universe.

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