National Aeronautics and
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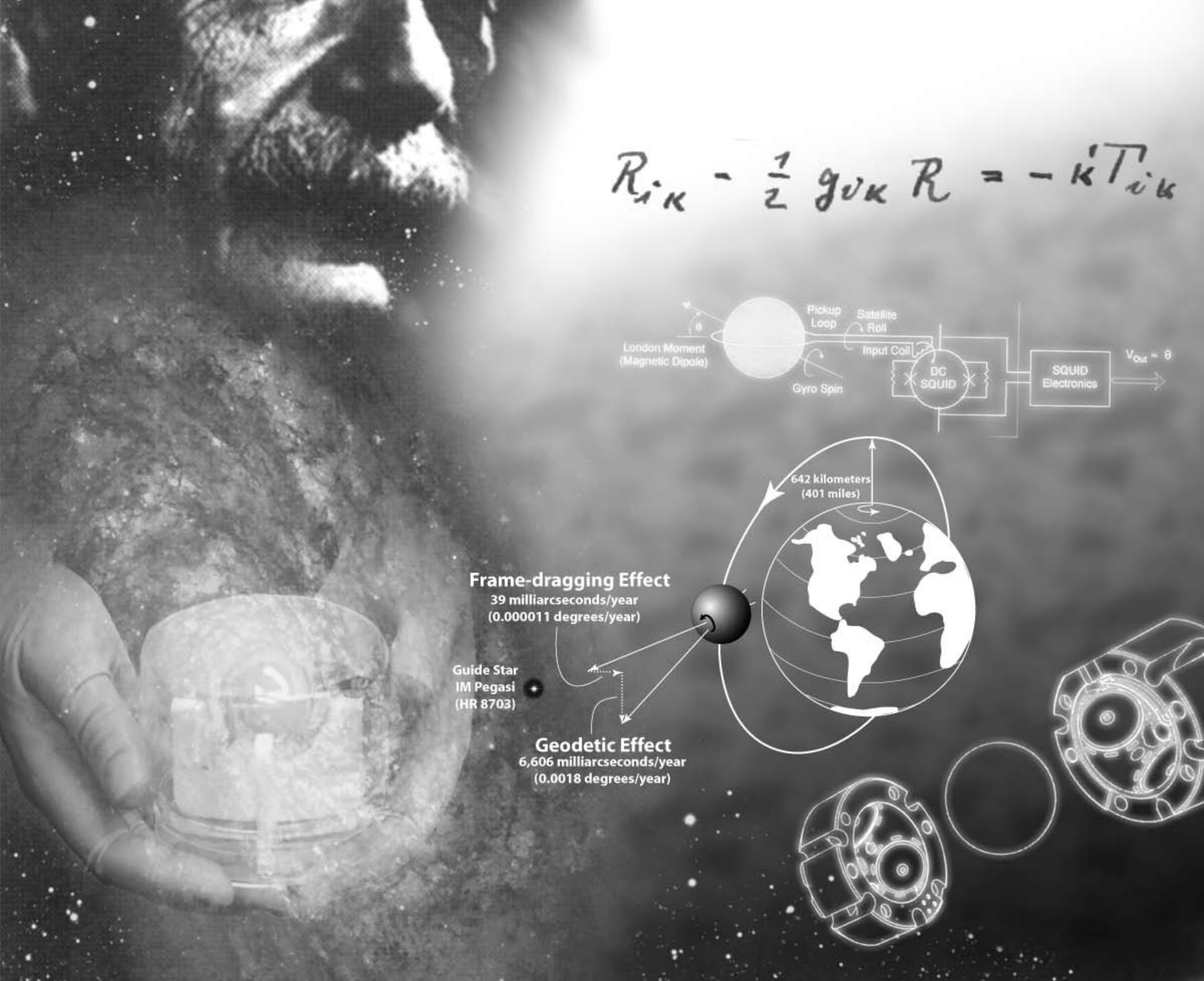
Educational Product	
Educators & Students	Grades 9-12

GRAVITY PROBE B

Examining Einstein's Spacetime with Gyroscopes

An Educator's Guide



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THIS EDUCATOR'S GUIDE ADDRESSES THE FOLLOWING NATIONAL SCIENCE EDUCATION STANDARDS:

CONTENT STANDARD A
* Understandings about scientific inquiry

CONTENT STANDARD B
* Motions and forces
* Conservation of energy and increase in disorder
* Interactions of energy and matter

CONTENT STANDARD D
* Origin and evolution of the universe

CONTENT STANDARD E
* Abilities of technological design
* Understandings about science and technology

CONTENT STANDARD G
* Science as a human endeavor
* Nature of scientific knowledge
* Historical perspectives

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An Introduction To Gravity Probe B

Examining the Fundamental Structure of the Universe

Gravity Probe B is a satellite-based experiment developed by NASA's Marshall Space Flight Center, Stanford University, and Lockheed Martin to test two extraordinary, unverified predictions of **Albert Einstein's General Theory of Relativity** (1916).

1) **How warped is "curved spacetime"?** - Einstein's theory predicted that the presence of a mass in space, such as the Earth, would warp local spacetime, creating a dip or curve in spacetime. Any matter or energy in Earth's local spacetime will reveal that curve.

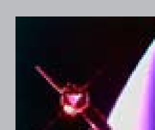
GEODETIC EFFECT

2) **Does the rotating Earth create "frame-dragging"?** - A few years after Einstein published his theory, two physicists predicted that the rotation of a mass in space would twist or drag the local spacetime frame around it. Any matter or energy in Earth's local spacetime should follow that twist.

GRAVITO-MAGNETIC EFFECT

Gravity Probe B's objective is to observe and measure these effects to the greatest precision ever attempted. Gravity Probe B has launched four ultra-spherical gyroscopes into low-Earth polar orbit (400 miles) for sixteen months. In orbit, each gyroscope's spin axis is monitored as it travels around the Earth through local spacetime. Scientists have predicted that each gyroscope's spin axis will turn 6,600 milliarcseconds per year due to the local spacetime curvature, and 41 milliarcseconds per year due to the frame-dragging effect.

GP-B Launches -- April 20, 2004



At 9:57:24 am (PDT) on Tuesday, April 20, 2004, the Gravity Probe B spacecraft had a picture-perfect launch from Vandenberg Air Force Base in Southern California. At approximately one hour eleven minutes, the spacecraft's solar arrays deployed, and the on-board cameras treated all viewers to the extraordinary sight of the separation of the spacecraft from the second stage rocket, with a portion of the Earth illuminated in the background. The Boeing Delta II rocket hit the exact center of the bullseye, placing the spacecraft in its target polar orbit 400 miles above the Earth.

Between April and August, GP-B was in the Initialization and Orbit Checkout phase, during which the four gyroscopes were spun up to 4,000 rpm and the spacecraft's attitude and systems were tuned in preparation for the 10-month science phase of the mission. In late August 2004, Gravity Probe B began collecting relativity data from all four gyroscopes. The data collection will continue through the summer of 2005, followed by a two-month final calibration of the science instrument.

From Newton's Gravity to Einstein's Curved Spacetime

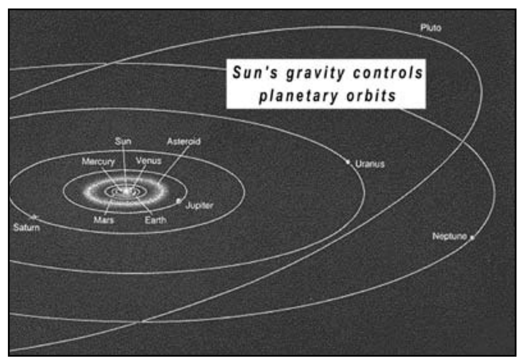
In Einstein's General Theory of Relativity, space is transformed from the Newtonian idea of a vast emptiness that has no effect on the motion of matter, to an invisible web of spacetime that grips matter and directs its course. Gravity is no longer simply a force that attracts matter; it is also the curve and warp of spacetime itself.

How did Einstein come to this idea of spacetime? What made him doubt that Newton's theory of gravity ruled the universe? And what exactly is "curved spacetime"? In this section, we learn about the two questions that propelled Einstein to question Newton's theory of gravity and drove Einstein to redefine our universe.

A. On The Road to Spacetime

Newton's theory of gravity (1687) is as familiar to us as walking down a hill. The invisible force of gravity reaches out from the Earth and pulls us down, one foot after the other. This force is especially noticeable if we try to go back up that hill – it makes every step a struggle. Gravity keeps coins in our pockets, pulls leaves to the ground, and pours coffee in our cup. It makes waterfalls fall and rivers flow to the oceans. It brings baseballs and basketballs and astronauts back to Earth.

Newton extended this idea beyond the Earth to include the planets and the solar system. The Sun's gravity reaches out across empty space and constantly pulls the planets towards it. The Sun's gravity also pulls comets around in elliptical orbits and keeps asteroids orbiting between Mars and Jupiter.



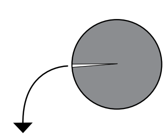
Newton's theory is such a clear explanation of all of these phenomena that one wonders why anyone would doubt it. What could be wrong with Newton's theory of gravity?

Question #1 – How Fast Is Gravity?

In Newton's Principia Mathematica (1687), he 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 assumed that the force of gravity ***traveled instantly*** across empty space from one mass to another.

What is an arcsecond?

Angles are measured in degrees, arcminutes and arcseconds. There are 60 arcminutes in one degree, 60 arcseconds in one arcminute, and 1,000 milliarcseconds in one arcsecond.



1˚ = 3,600 arcsecs

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 light propagated at a finite rate in a vacuum -- 299,792 km/sec (185,871 miles/sec). In 1905, Einstein's theory of special relativity was based on the idea that this rate was the speed limit for all matter and energy in the universe. If gravity was a force that transmitted between masses in the same way light propagated through space, the force of gravity should be equally restricted to 299,792 km/sec. While moving nearly three-hundred-thousand kilometers each second is extremely fast, it is not instantaneous.

NO HYPOTHESIS

In the `Principia' (1687), Newton states that "there is a power of gravity pertaining to all bodies, proportional to the several quantities of matter which they contain." As the story goes, when Newton was questioned about how this "power of gravity" transmitted from one body to another, he responded, "I make no hypothesis."

Just look at the Sun's light crossing our solar system. Light, in the form of photons, flies out of the Sun toward the inner and outer planets. These photons cross enormous distances very rapidly. But even at this rate, minutes and hours pass before they reach the planets (see table). If the force of gravity could travel no faster than the speed of light, then gravity was certainly not crossing space instantaneously, as Newton suggested.

How Fast Does The Sun's Gravity Reach the Planets?

	NEWTON	EINSTEIN
Mercury	*instantly*	*3.2 minutes*
Earth	*instantly*	*8.3 minutes*
Jupiter	*instantly*	*45 minutes*
Pluto	*instantly*	*5.5 hours*

Was Newton's theory wrong, even though it appeared to mostly agree with the orbits of the planets? Or was Einstein's conclusion mistaken, meaning that gravity was not like other forces and it actually could transmit faster than light? Or could gravity be understood in another way?

This contradiction prompted Einstein to search for a new theory of gravity. He wrote,

> *In 1907,...I realized that all the natural phenomena could be discussed in terms of special relativity except for the law of gravitation. I felt a deep desire to understand the reason behind this.... It was most unsatisfactory to me that, although the relation between inertia and energy is so beautifully derived [in special relativity], there is no relation between inertia and weight.*
>
> -- From Einstein's Kyoto lecture in "Subtle is the Lord", Abraham Pais, p.179

Einstein's greatest breakthrough in this quest came when he realized that the "equivalence principle" allowed him go beyond the concepts of inertia and weight when explaining how gravity makes things fall.

Question #2 - What About The Equivalence Principle

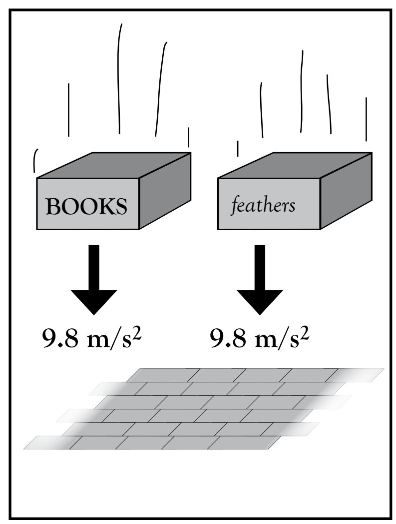
One of the most peculiar principles of physics is also one of the most common experiences of our daily lives. Every day we drop things or put things down: coins in our pocket, keys on the table, clothes on the chair. We take for granted that when we release these objects from our hand, gravity will pull them down. Yet, what is peculiar about these events is that all of these objects, regardless of their mass, fall at exactly the same rate. Even though a box of books and a box of feathers feel dramatically different in our hands, they fall to the ground at exactly the same rate.

This is phenomenon is one aspect of the Equivalence Principle – the idea that all masses accelerate down at the same rate in a gravitational field despite any difference in their mass. Apollo 15 Astronaut Dave Scott demonstrated this by dropping a hammer and a feather on the moon (where there is no air resistance) and seeing them hit the surface at the same time.

Gravity Pulls Harder on Some Things?

What exactly is happening here? How can two objects with dramatically different masses fall to the ground at the same rate?

The answer to this paradox lies in the remarkable balance between the amount that gravity pulls on an object (the object's weight) and the amount that the object inherently resists this pull (i.e., the object's inertia).

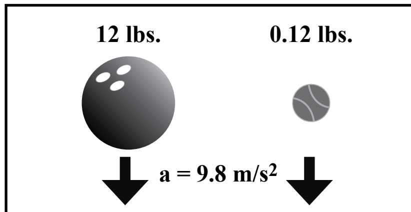


Take two objects of significantly different mass, such as a bowling ball and a tennis ball. The bowling ball (12 lbs., 5 kg) weighs about 100 times more than the tennis ball ($^{1}/_{8}{}^{th}$ lb., .05 kg). The weight of each object is different because the mass of each object is different. The force of gravity on each ball is proportional to how much mass is in each ball. This is a basic assumption in Newton's theory of gravity.

Of course, it would be reasonable to assume that if the force of gravity were different for each ball, then the balls would fall to the ground at different rates. But that is not what happens (at least, not in a vacuum or airless environment). When the bowling ball and the tennis ball are released above the Earth at the same time, they accelerate to the ground at the same rate. How could this be?

Newton answered this question by postulating that the bowling ball and the tennis ball resist acceleration by different amounts. The bowling ball, having a greater mass, has a greater resistance to acceleration. The tennis ball, having a smaller mass, has much less resistance to gravity's acceleration.

So even though gravity pulls harder on the bowling ball than the tennis ball, the bowling ball has greater resistance to this pull. The result is that the bowling ball accelerates to the ground at 9.8 m/s^2 -- the exact same rate as the tennis ball. In every object, the force of gravity and the object's inertia balance each other out, meaning that all objects accelerate to the ground at the same rate regardless of their mass.



If both balls fall at the same rate, but weigh different amounts, then the force acting on them must be different!

This is a tidy explanation as far as it goes. However, there is no explanation as to ***why*** this is true. Why is do these two things balance out for every object in the universe?

Einstein's response to this question was to wonder if there could be a deeper reason for the fact that all objects fall at the same rate in a field of gravity. Could there be an alternative explanation for this remarkable behavior? An explanation of what "gravity" really was?

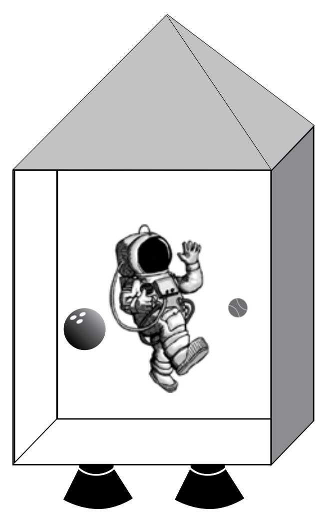
Einstein's answer is so counter-intuitive that it requires careful attention and a bit of time to get comfortable with. Einstein's answer was the second aspect of the Equivalence Principle -- that our experience of gravity is equivalent to our experience of acceleration. Therefore gravity is simply curved spacetime.

In the next section, we see how Einstein let an imaginary ride in an elevator take him to this physical universe in which we did not even know we lived in which the motion of objects is ruled by the curvature of spacetime.

Free-Fall Equals Floating In Space

Return to the bowling ball and tennis ball. Instead of simply dropping them on the ground, imagine stepping into an elevator to repeat this dropping test. The special thing about this elevator is that as soon as you step inside and the doors close, the elevator begins falling to the ground. Once you get over your shock at this development, you notice something surprising – the bowling ball and the tennis ball are floating next to you. In fact, you are also floating inside the elevator as you all fall to the ground.

What you are experiencing is free-fall. What is amazing is that this experience is identical to the experience of astronauts in space. When one is floating in space, far from any gravitational fields, the experience is no different from free-falling on Earth in the Earth's gravitational field. When Einstein realized this, he called it his "happiest thought":



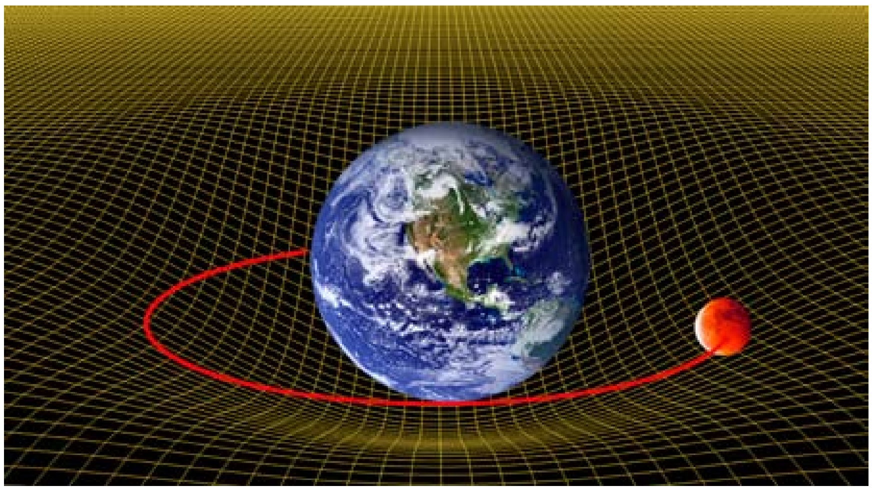
> *For an observer falling freely from the roof of a house, there exists - at least in his immediate surroundings - no gravitational field. Indeed, if the observer drops some [masses], then these remain to him in a state of rest....*

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.

B. A New Understanding: Curved Spacetime

In 1916, Einstein presented the world with this new understanding of the universe - his General Theory of Relativity. In his 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 called spacetime whose shape is curved and twisted by the presence and motion of matter and energy.

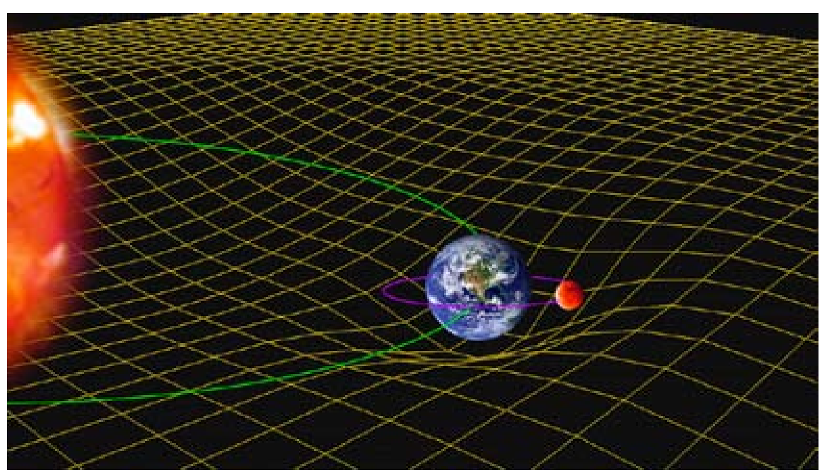
Spacetime is curved around any mass. The presence of planets, stars and galaxies warps the fabric of spacetime in a manner similar to a bowling ball warping a spandex sheet. The mass of the ball stretches the fabric and creates a dip or curve that gradually decreases the farther one moves from the mass.



When a smaller mass passes near a larger mass, it accelerates towards the larger mass because spacetime itself is curved toward the larger mass. The smaller mass is not "attracted" to the larger mass by any force. The smaller mass simply follows the structure of curved spacetime near the larger mass. For example, the massive Sun curves spacetime around it, a curvature that reaches out to the edges of the solar system and beyond. The planets orbiting the Sun are following the curvature of spacetime by the Sun.

Space vs. Spacetime?

In Newton's physics, space and time were separate concepts. Position is simply described by the three spatial coordinates (x, y, z). In Einstein's physics, space and time are combined into spacetime so that when describing the position of an object one must include all four dimensions (x, y, z, time). Why did Einstein find this necessary? Because he realized that the passage of time was relative. By including the time coordinate in the description of position, one was describing time relative to a frame of reference, which is absolutely critical in Einstein's relativity.



Falling in Curved Spacetime

Here on Earth, all matter falls straight down because of the same curvature of spacetime. However, understanding how this happens requires a different perspective than that provided by a dented bed sheet. For this visualization, we need a three-axis graph and a steady hand.

On our three-axis graph, we display three dimensions -- but not the usual x-, y-, and z- dimensions. This graph shows spatial motion only in the x-y directions, or on the horizontal plane. The vertical axis represents the passage of time. *(Figure 1)* While it would behoove us to draw a four-dimensional graph, that would take a sleight of hand only mathematical artist M.C. Escher could master!

On this graph, we plot the motion of objects just like any other three dimensional graph. Each point is plotted using three coordinates -- x, y, and time. What is unusual about this graph is that even when something appears to not be moving to us, it is moving on the graph! Why? Because even when we are standing still, time is passing. So even when we are still, we are moving through time. *(Figure 2)*

On our graph, this motion through time traces a straight vertical line. One example of this straight vertical motion is the motion of the Earth (relative to an Earth-based frame). The Earth sits at the intersection of the x-y axes and moves straight up as time passes. *(Figure 3)*

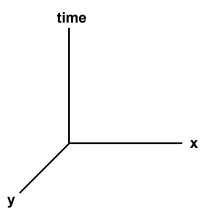


Figure 1

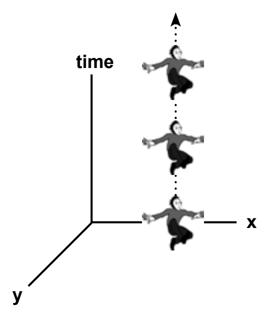


Figure 2

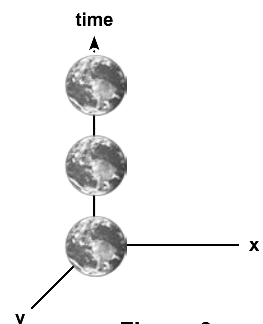
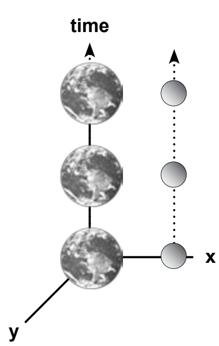


Figure 3

Now consider the path of an object near the Earth. If we hold a ball up off to the side of the Earth, it also traces a straight vertical line on our graph as time passes. (Holding a ball “up” may be “overhead” to us, but it is “out to the side” from the Earth’s perspective.) *(Figure 4)*

Now what happens when you release that ball? From our perspective on Earth, it appears to fall. But on the graph, it does something much weirder. *(Figure 5)* Instead of following a straight line up, it bends toward the Earth as time passes. If you dropped the ball off a tall building, after one second it would be closer to Earth and after two seconds it would intersect the Earth as they both moved through time.

Figure 4



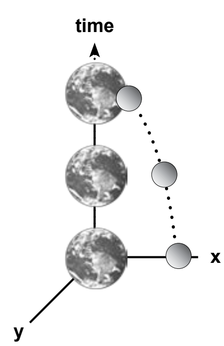


Figure 5

Why did the ball's path on our spacetime graph bend toward the Earth? It was not necessarily the force of gravity, Einstein claimed. It was the warp of spacetime around the Earth. As you can see on the graph, spacetime near the Earth is apparently bent in the direction of the Earth. *(Figure 5)* As objects travel in free-fall along the time dimension, they follow the warp of spacetime toward Earth.

Objects fall on Earth because they are following the warp of spacetime created by the mass of the Earth. We do not normally see this because we are so embedded in our conception of three spatial dimensions. But when looked at through the lens of this graph, warped spacetime is as obvious as falling off a horse.

C. The Tests of the Past Century

The physics world and the world in general were astounded by Einstein's claims. Einstein described himself as "zufrieden aber ziemlich kaputt" ("content, but rather worn out") after his ten-year struggle to find a new theory of gravity.

For many, it was incomprehensible that the gravitational force that we knew so well could be alternatively described as a geometry of spacetime curved by the presence of matter. The only way that Einstein's theory of curved spacetime could be accepted would be to test it. As in all science, only empirical experiments with actual observations and measurements would convince people that Einstein was right.

Fortunately, several ways to test his theory presented themselves soon after Einstein's revelations. Einstein actually conducted the first of these himself mere days before publishing his theory. It concerned the unexplained extra precession of Mercury's orbit, a mystery that was fifty years old.

1) The Anomalous Precession of Mercury's Orbit

In the early days of astronomy, maps of the solar system described the orbits of planets as perfect circles. Later, astronomer Johannes Kepler realized that these orbits were not circles, but ellipses. More interestingly, Mercury's elliptical orbit was observed to be precessing slightly. Mercury did not follow the exact same path each time it orbited the Sun; its orbit was turning at the miniscule rate of 574 arc seconds per century ($\sim{}^{1}/_{6}{}^{\text{th}}$ of a degree)

Mercury's orbital precession was not an unusual phenomenon. Most planets in the solar system precess as they travel around the Sun. What was puzzling about Mercury was that Newton's theory of gravity did not account for it quite right. When Simon Newcomb used Newton's equations to calculate the effect that all the other planets had on Mercury, Newton's equations came up 43 arcseconds short.

Where were the missing 43 arcseconds? Some astronomers had proposed that a smaller, unseen planet named "Vulcan" was orbiting inside Mercury and creating this anomalous precession. Others guessed that it had something to do with interplanetary dust or the possible oblateness of the Sun.

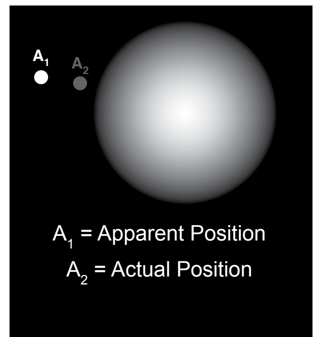
However, when Einstein applied his equations to this mystery in 1915, he said "for a few days, I was beside myself with joyous excitement."(1) His resutls precisely predicted Mercury's precession and his General Theory of Relativity won its first major victory.

(1) -- "Subtle is the Lord", Abraham Pais, p.253

2) Starlight Deflection During Solar Eclipse

Another major victory was soon to come. In 1919, the British astronomer Sir Arthur Eddington set out to test one of Einstein's central claims – that all matter and energy moving through the universe must follow the curves of spacetime. This includes light rays as they emerge from distant stars and make their way across the universe to our Earth-based telescopes and eyes. When the light passes near a massive body, such as a galaxy or our Sun, its path deflects slightly to follow the curvature of spacetime around the massive body.

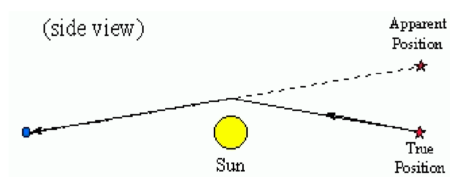
For example, this means that if a star is obscured from our view on Earth by an intervening mass (e.g., the Sun, a galaxy), it should still be possible to see the star because its light bends around the mass and reach Earth.



The Sun's mass bends the starlight slightly, making the star appear displaced outward. In fact, the star is closer to the edge of the Sun than it appears.

Eddington, with the help of Astronomer Royal Frank Dyson, organized simultaneous expeditions to South America and West Africa to observe and photograph a solar eclipse. The solar eclipse gave Eddington the opportunity to see stars that were close to the edge of the Sun by blocking out the Sun's intense light. According to the theory, these stars would appear in a slightly displaced location than they usually did due to the Sun's mass curving spacetime.

Eddington proved this by photographing the same area of sky later in the year and comparing the locations of the stars. When the Sun had intervened between the Earth and the distant stars, it had curved spacetime and bent the starlight. This meant that the stars appeared to have shifted outward when the Sun was there.

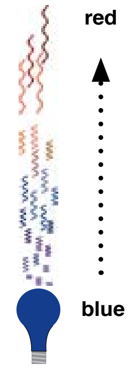


Since that time, this experiment has been repeated with higher and higher precision using light rays and radio waves, always confirming Einstein's prediction. Between 1969 and 1975, twelve measurements were made using radio telescopes to measure the deflection of radio waves from a distant quasar. These measurements matched general relativity's predictions within 1%.

2) Gravitational Redshift

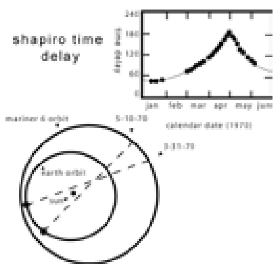
Two other aspects of Einstein's theory that have been tested include the gravitational redshift and the Shapiro time-delay. In the first case, light is predicted to lose energy as it emerges from a gravitational field. When light loses energy, its wavelength becomes longer and the color of the light shifts toward the red end of the spectrum (therefore called the "redshift"). In 1960, physicists Robert Pound and Glen Rebka were able to detect the redshift of high-energy gamma rays in an elevator shaft at Harvard University. Their measurement agreed with Einstein's predictions to within 10%.

The Gravity Probe A experiment (also known as the Vessot-Levine test) made the most accurate measurement of gravitational redshift to date. The experiment consisted of a hydrogen maser clock inside a rocket that flew in an arc reaching an altitude of 10,000 km above the Earth. As predicted, the clock ran just a little bit faster as it rose into the weaker gravitational field away from Earth than it did on the surface of the Earth, an effect analagous to the redshift of light. After correcting for the fact that rapidly moving clocks also run slower relative to those on the ground (see Special Relativity), the GP-A result agreed with general relativity to within .01%



3) Shapiro Time-Delay

In the second case, Irwin Shapiro predicted that light waves (or any electromagnetic waves) would be delayed when passing through a gravitational field. The waves would have to follow the curves in spacetime that would make their paths longer than expected. This would create a delay in the expected transmission time of the electromagnetic waves.

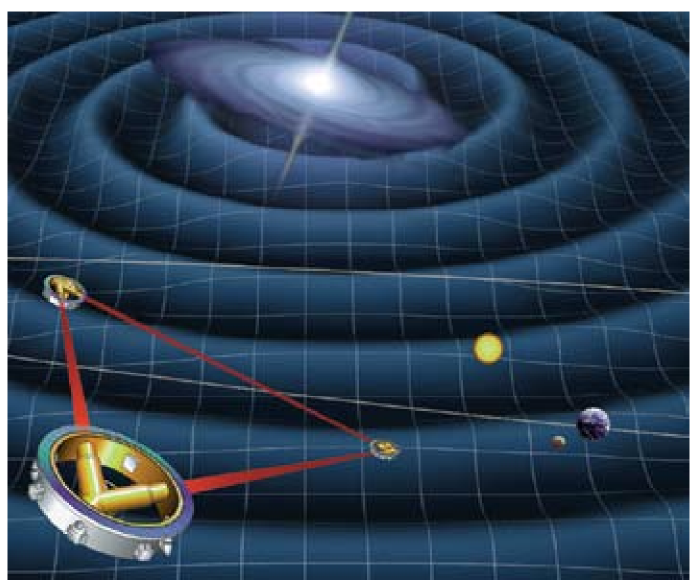


Since 1964, scientists have used radio telescopes to perform "radar ranging" on various objects whose distance is precisely known, including the planets Mercury and Venus. Signals have also been bounced off the Mariner 6 and Mariner 7 spacecrafts as they orbited Mars and off a transponder left on the surface of Mars by NASA's Viking lander. This last experiment confirmed Einstein's prediction to within 0.5%.

So in the century following the publication of the General Theory of Relativity, Einstein has passed all these tests with flying colors. Every experiment has agreed with his predictions and confirmed his claim that the universe is not ruled by a "force of gravity" but by the curvature of spacetime. What more needs to be done? What could be the role of Gravity Probe B?

Searching for Gravity Waves

A final note about the instant propagation problem. According to Einstein's theory, the force of gravity does not travel across space instantly. It travels at the speed of light in the form of gravity waves. These gravity waves should be detectable following a massive gravitational event, such as an exploding supernova or the collapse of a star into a black hole. While these have not been detected yet, both the LIGO and LISA missions hope to provide the first empirical evidence for this phenomena within the next decade. These missions are constructing very large ultra-sensitive antennas -- LIGO spans 4 km based on the ground; LISA will span 5,000,000 km in space -- that will vibrate when a gravity wave passes by.



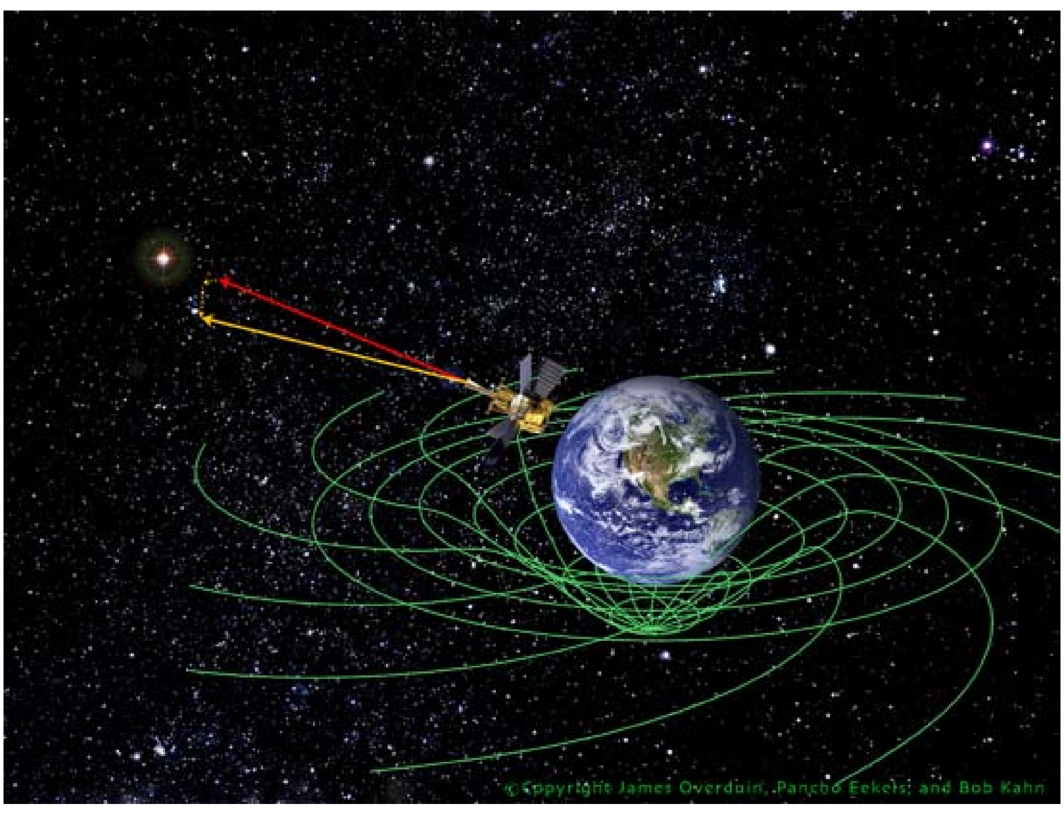
D. Frame-Dragging & The Role of Gravity Probe B

The role of the Gravity Probe B (GP-B) experiment is two-fold. First, this experiment will provide the most precise measurement of the curvature of spacetime around the Earth ever taken. Second, GP-B will be the first experiment to directly test a prediction of general relativity that has completely eluded scientists since 1918 – the phenomenon of "frame-dragging."

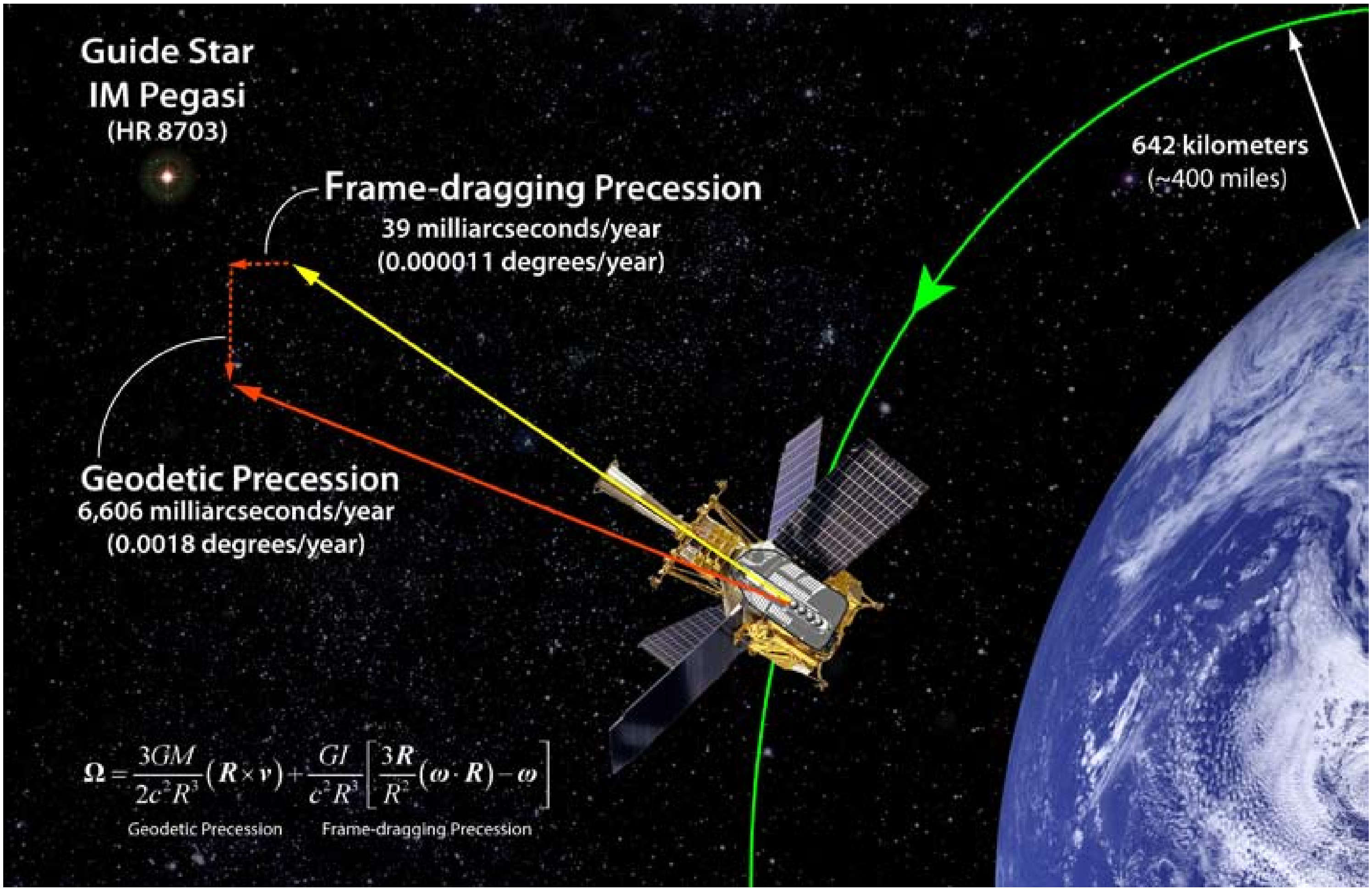
A few years after Einstein developed his theory of curved spacetime, Austrian physicists Joseph Lense and Hans Thirring predicted that a mass could deform spacetime in a second way - through "frame-dragging" (1918). They proposed that the rotation of planets and stars or any rotating mass twists the structure of spacetime near that mass. In more technical terms, a rotating mass carries a gravitomagnetic current, not unlike an electric current. As it rotates, this current disturbs the space around the mass including any objects in that space. 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, or a galaxy.

Frame-dragging has never been seen in the universe with any degree of certainty. If GP-B's investigation of frame dragging confirms its existence, it could help solve numerous mysteries about our universe from explaining the origin of massive energy jets coming out of quasars to the fundamental question of why we experience inertia.

The GP-B satellite measuring the frame-dragging of local spacetime caused by the Earth's rotation.



“Seeing” Spacetime with Gyroscopes



14 MONTHS	Duration of the mission
39 MILLI-ARCSECONDS	Predicted drift of gyroscopes due to frame-dragging
0.5 MILLI-ARCSECONDS	Margin of error for GP-B
1.4 x 10^{-7} DEGREES	Margin of error in degrees
400 MILES HIGH	Orbital altitude of satellite
-271.2° CELSIUS	Temperature of liquid helium (1.8 K)

GRAVITY PROBE B FAST FACTS

A near-perfect, spherical gyroscope orbits in spacetime 400 miles above the Earth. At the beginning of the mission, the gyroscope’s spin axis points at IM Pegasi, a distant guide star. After one year, theoretical calculations predict that the gyroscope’s spin axis orientation will deflect in two directions: 6,606 milliarcseconds vertically, in the plane of the spacecraft’s orbit, due to the curvature of local spacetime—called the geodetic effect;” and 39 milliarcseconds horizontally, in Earth’s equatorial plane, due to frame-dragging—the twisting of local spacetime by a rotating mass such as the Earth.

1.5 INCHES	Diameter of each gyroscope
3 x 10^{-7} INCHES	Asphericity of gyroscopes
0.001 INCHES	Space between spinning gyroscope and housing
9 FEET	Height of dewar containing gyroscopes
645 GALLONS	Capacity of dewar
44 YEARS	Years that GP-B was in development

A. The Concept of Gravity Probe B

According to Einstein's General Theory of Relativity (1916), all planets and stars reside in an invisible, intangible structure of spacetime. The Earth, like all masses and energy, affects local spacetime in two ways. Earth's presence warps or curves spacetime around it, and Earth's rotation drags or twists the local spacetime frame with it (called "frame-dragging").

How could one test Einstein's theory? How could one "see" this invisible structure and measure the shape and motion of this intangible spacetime?

In 1960, Stanford University physicist Leonard Schiff and his colleagues were discussing the possible scientific benefits of creating a perfectly spherical gyroscope. Certainly this perfect gyroscope could improve navigation of planes, rockets and satellites. But Schiff proposed something else - a way to "see" local spacetime.

Schiff suggested that if they placed a near-perfect spinning gyroscope in spacetime above the Earth and monitored the direction its spin axis pointed, the floating gyroscope could show them the shape and behavior of our invisible spacetime frame. The experiment would only work with a near-perfect gyroscope, as the effects of spacetime's curvature and motion were predicted to be microscopically small.

Why a gyroscope? Gyroscopes, or any spinning object, remain oriented in the same direction as long as they are spinning, a property called rotational inertia. A common example of this inertia is a spinning top. It balances on its end while spinning, yet topples over when friction slows it down. While it spins, its rotational inertia keeps it pointed straight up, oriented in its original direction.

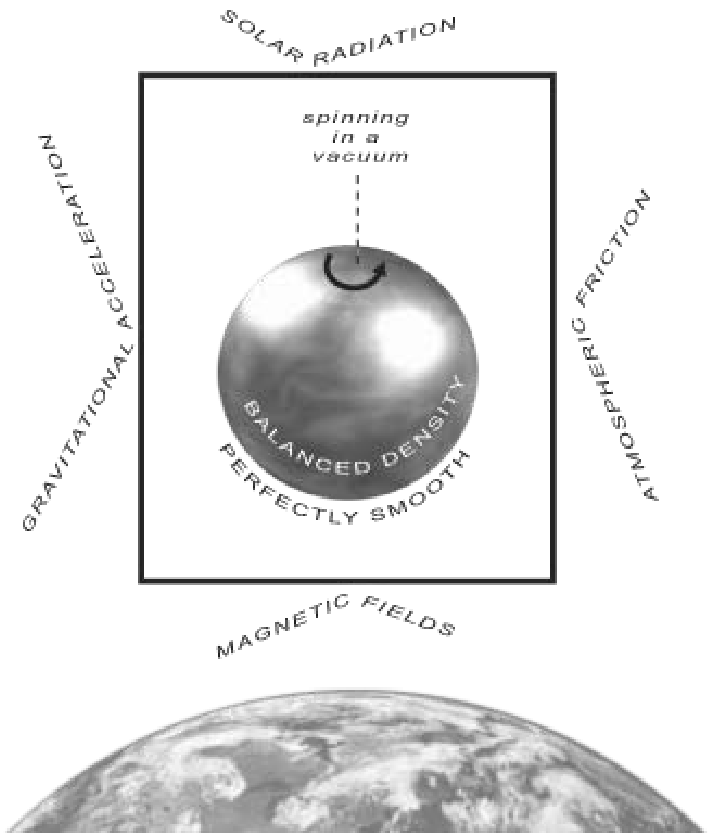
Accordingly, if a top was spinning in the near-vacuum of space, it would remain constantly oriented in its original direction, since there would be no forces to slow it down. Our Earth is a prime example of this. The Earth's axis is oriented 23.5 degrees from the plane of the ecliptic, relative to the Sun. It has remained in this orientation due in part to its rotational inertia.

ROTATIONAL INERTIA

The resistance that a mass exhibits to having its speed of rotation altered by the application of a torque (turning force); any spinning mass will continue to spin as long as no outside force acts upon it.

If a perfectly-spherical, spinning gyroscope floated above the Earth in spacetime, and it was protected from any external forces that could re-orient it (*e.g., gravity, solar radiation, atmospheric friction, magnetic fields, electrical charges*), and any internal imbalances were removed (*e.g., imperfect shape, unbalanced density, surface imperfections*) it would remain pointing in its original direction. The only thing that could alter its spin orientation would be the structure of spacetime itself.

If the local spacetime in which the gyroscope was floating was curved or was twisting, the gyroscope's orientation would change to follow this curve or twist. If we could monitor this change in orientation, we could "see" the shape and behavior of spacetime itself! This is the mission of Gravity Probe B: to "see" our local spacetime, and measure it more precisely than any experiment in history.



EARTH'S PRECESSION

Like all spinning tops or gyroscopes, the Earth's axis does move slightly while it spins - a motion called "precession". Every 26,000 years, the Earth's axis "precesses" in a complete circle, 23.5 degrees from normal to the plane of the elciptic. While the Earth's current "North Star" is Polaris, in 13, 000 years it will be Vega. Then 13,000 years later, Polaris again will be our North Star.

Compared to the Earth, Gravity Probe B's gyroscope hardly "precesses" at all. For this experiment to work, it must stay within two ten-millionths of a degree of its original orientation (<0.00000014˚ of precession)!

B. The Mechanics of Gravity Probe B

The Gravity Probe B mission plan is as follows:

1. Place a satellite into polar orbit. Inside the satellite are the four gyroscopes and a telescope (GP-B uses four gyroscopes for redundancy).

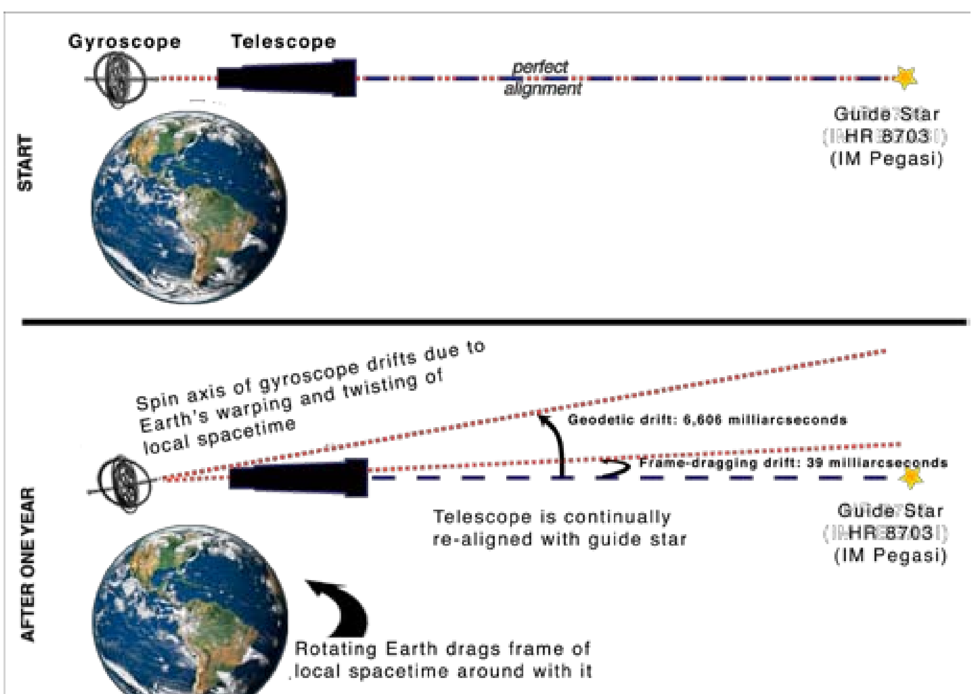
2. Point the telescope at a distant star (called the "guide star"). GP-B aligns the telescope by turning the satellite because the telescope is fixed within the satellite.

3. Align the spinning gyroscopes with the telescope so that each spin axis also points directly at the guide star.

4. Remove any external forces (pressure, heat, magnetic field, gravity, electrical charges) so the gyroscopes will spin unhindered, in a vacuum within the satellite and free from any influence from the satellite itself.

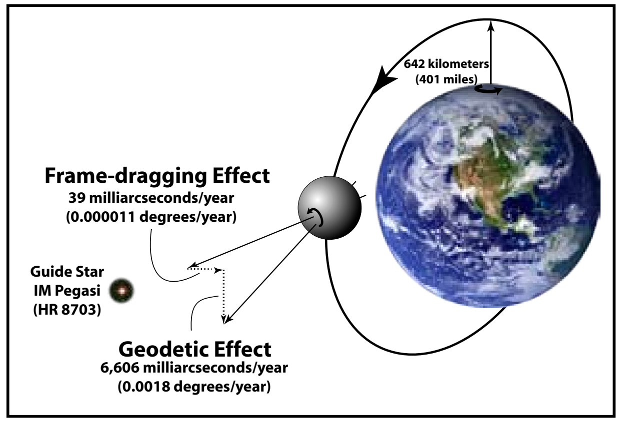
5. Monitor the spin axis orientation of the gyroscopes for one year. Keep the telescope fixed on the guide star. Measure any space that opens up between the telescope's orientation and each gyroscope's spin axis. If local spacetime around the Earth is curved and frame-dragging occurs, the gyroscopes should slowly drift during this time, revealing the shape and motion of local spacetime.

According to Schiff's calculations, with the gyroscopes and satellite orbiting 400 miles (640 km) above the Earth's surface, the orientation of each gyroscope's spin axis should shift **6606 milliarcseconds per year due to the local spacetime curvature** and should turn **39 milliarcseconds per year due to the frame-dragging** effect. In other words, Gravity Probe B intends to use gyroscopes and a telescope orbiting above the Earth to measure two microscopic angles, each predicted to be a tiny fraction of a single degree.

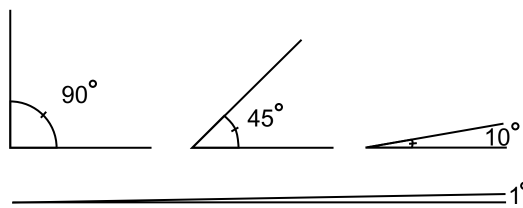


C. Two Microscopic Angles: How Small is Small?

The central challenge of the Gravity Probe B mission is to build a gyroscope, telescope and satellite that can precisely measure two miniscule angles. Because these angles are so small, GP-B has very little margin of error. The telescope must point to within one milliarcsecond of the exact center of the guide star. GP-B must know the gyroscope's orientation to within one-half of a milliarcsecond (~ one ten-millionth of a degree)!

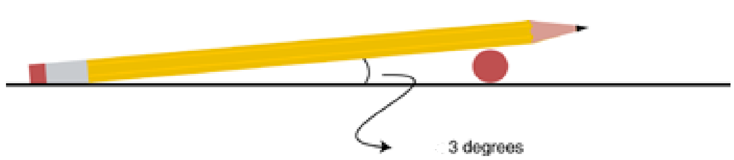


These angles are almost too small to comprehend. We know that street corners make 90 degree angles, and the diagonal of a square is 45 degrees. A ramp into a building or up to the curb is usually between five and ten degrees. Walking on a slope of one or two degrees seems like practically nothing - it feels like walking on flat ground.



However, a slope (or angle) of one degree is like climbing Mount Everest compared to the angles GP-B is trying to measure. The "curvature angle", 6,506 milliarcseconds, rises less than two-thousandths of one degree. And the "frame-dragging angle", which is 39 milliarcseconds, is over 170 times smaller than that, opening a mere 0.000018 degrees (1.2 hundred-thousandths of a degree). If you "climbed" a slope of 39 milliarcseconds for 100 miles, you would be only *one inch higher* than you were when you started out!

One way to see how small these angles are is to lay a pencil across another pencil. Look at the angle between the leaning pencil and the table top. This angle is fairly small - about three degrees. To imagine how small 41 milliarcseconds is, break this angle into about 250,000 equal pieces! GP-B must measure this angle within a precision of 0.5 milliarcseconds - an angle 20,000,000 times smaller than the angle between the pencil and the table top!



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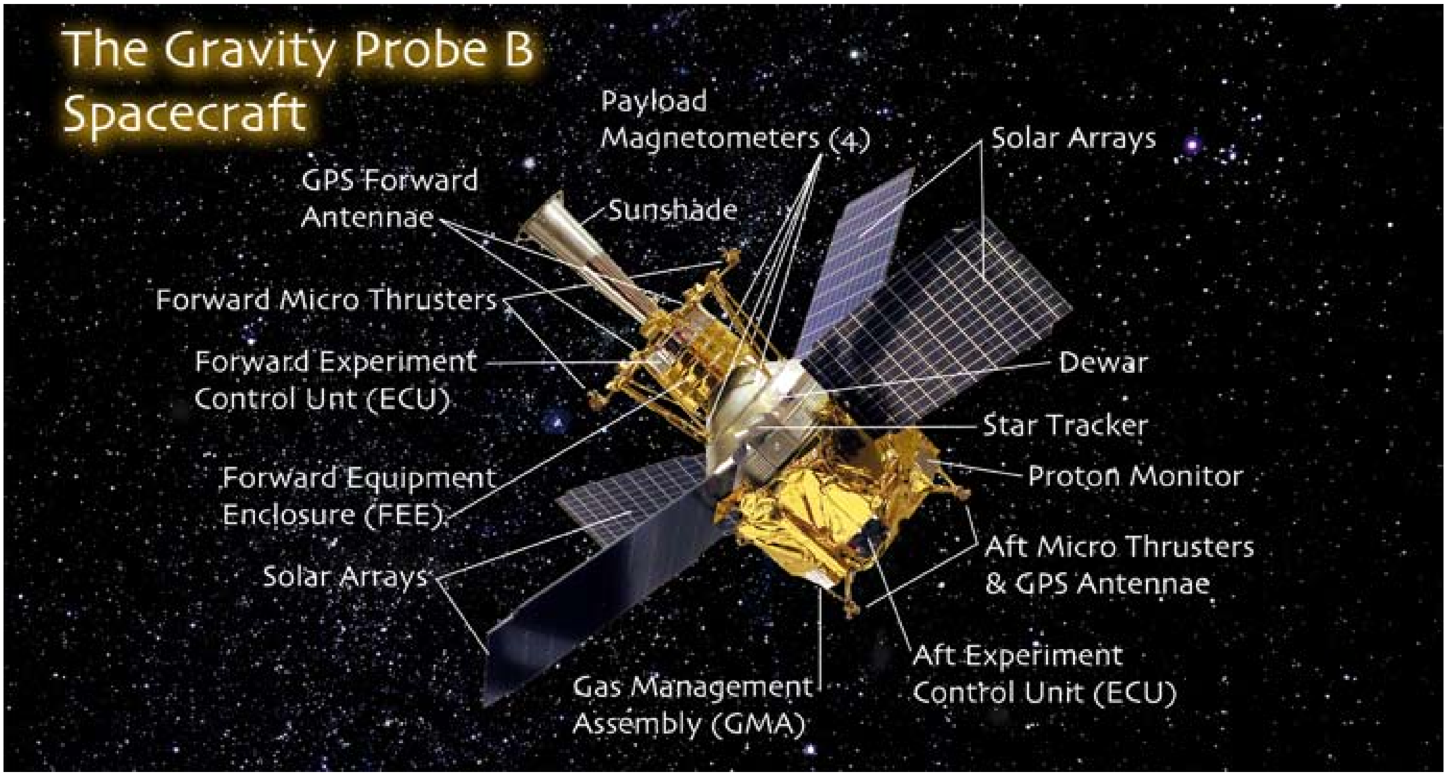
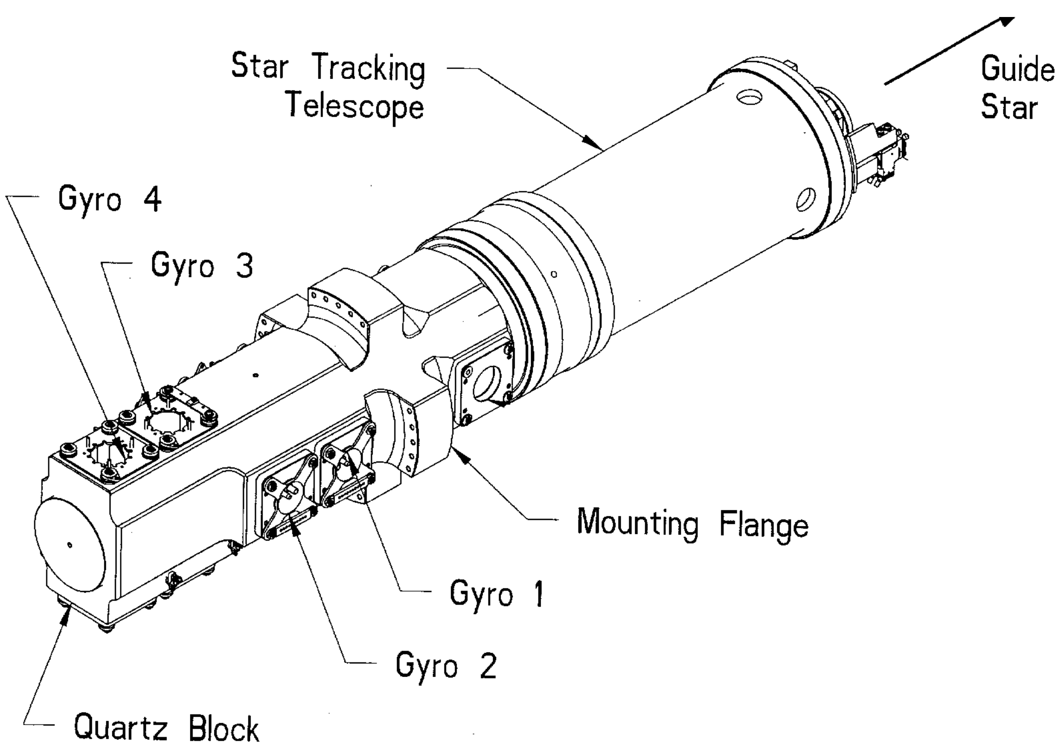

The Gravity Probe B
Spacecraft
Payload
Magnetometers (4)
Solar Arrays
GPS Forward
Antennae
Sunshade
Forward Micro Thrusters
Forward Experiment
Control Unt (ECU)
Dewar
Star Tracker
Forward Equipment
Enclosure (FEE)
Proton Monitor
Aft Micro Thrusters
& GPS Antennae
Solar Arrays
Aft Experiment
Control Unit (ECU)
Gas Management
Assembly (GMA)


Gravity Probe B
Payload
Components
Dewar & Probe
Science
Instrument
Assembly
Telescope
Quartz Block
Image Divider &
Detector Package
Assemblies
Detector Mount Assembly
Gyro Housing Assembly
Gyroscope Rotor & Housing
SQUID with Housing

The Gravity Probe B Science Instrument

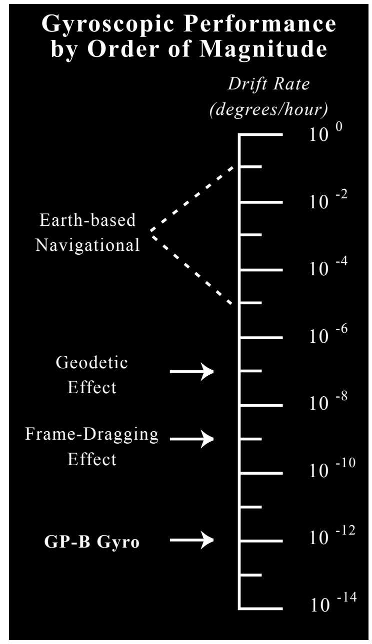
To test Einstein's theory of general relativity, Gravity Probe B must measure two miniscule angles with a spinning gyroscope floating in space. While the concept of Gravity Probe B is relatively simple in design, the technology required to build it is some of the most sophisticated in the world. Scientists and engineers from Stanford University, NASA's Marshall Space Flight Center, and Lockheed Martin Corporation have drawn from a diverse array of physical sciences, and have invented much of the technology that makes the mission possible. In fact, much of the technology did not even exist when Leonard Schiff conceived of the experiment in the early 1960's.

The Gravity Probe B science instrument takes the shape of a long rectangular block with four gyroscopes lined up behind a telescope that peers out the top of the Gravity Probe B satellite. Each gyroscope is suspended in a quartz housing, surrounded by a metal loop connected to a SQUID to monitor its orientation. The fused quartz gyroscopes sit in a fused quartz block that is bonded to the fused quartz telescope. These three components make up the Science Instrument Assembly (SIA).



A. The World's Most Perfect Gyroscope

To measure the microscopic angles that Leonard Schiff calculated based on Einstein's general theory of relativity (6.6 arcseconds per year and 41 milliarcseconds per year), Gravity Probe B needed to build a near-perfect gyroscope—one that would not drift more than one hundred-billionth of a degree from vertical each hour that it was spinning. This is an especially stiff challenge, given that all gyroscopes tend to drift slightly while they are spinning. Even the most sophisticated Earth-based gyroscopes, found in missiles and jet airplanes, drift seven orders of magnitude more than GP-B could allow.



What creates drift in even the best gyroscopes? Three physical characteristics of a gyroscope can cause its spin axis to drift: 1) an imbalance in mass or density distribution inside the gyroscope, or 2) an uneven or asymmetrical surface on the outside of the gyroscope causing air friction, or 3) friction in the suspension system of the gyro rotor. This means the GP-B gyroscope has to be perfectly balanced and homogenous inside, cannot have any rough surfaces outside, and that the gyro suspension system is virtually frictionless.

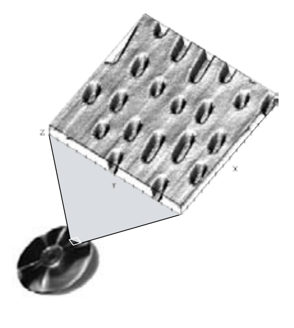
After years of work and the invention of numerous new technologies, this is the result: a homogenous 1.5-inch sphere of pure fused quartz, polished to within 100 atomic layers of perfectly smooth. It is the most spherical object ever made, topped in sphericity only by neutron stars!

Inside, the gyroscope is solid fused quartz. It was carved out of a pure quartz block that was crystalized in Brazil, ground into a powder, and then baked in a laboratory in Germany. Its interior parts are all identical to within two parts in a million (that's like having 999,998 identical siblings out of 1,000,000 people!)

On its surface, the gyroscope is spherical to within 20 nanometers (20 billionths of a meter). This means that every point on the surface of the gyroscope is the exact same distance from the center of the gyroscope to within 3 ten-millionths of an inch.

Gravity Probe B gyroscope (rotor) with quartz housing halves. Each milky-colored quartz rotor is coated with a sliver-thin layer of niobium, a superconducting metal. Inside each housing, six electrodes electrically suspend the gyroscope allowing it to spin freely at 4,000 rpm. Channels are cut in the quartz housing to allow helium gas to start the rotor spinning. A wire loop embedded in the housing acts as a SQUID to detect any change in direction of the gyroscope's axis.

Here are two ways to imagine how smooth this is. First, compare the GP-B gyroscope's smoothness with another smooth object - a compact disk. CD's and DVD's both appear and feel incredibly smooth. The pits on the compact disk's surface, which carry the digital information, are little more than one-hundred-thousandth of an inch deep (one micron). However, compared to the GP-B gyroscope, the surface of a CD is like sandpaper! The bumps and valleys on the surface of the GP-B gyroscope are 100 times smaller than those on a CD. Viewed at the same magnification, one could barely see any imperfections on the gyroscope's surface!



A magnified view of a CD reveals pits in the surface. Viewed at the same magnification, one would barely see any imperfections on the gyroscope's surface!

Second, imagine the GP-B gyroscope is enlarged to the size of the Earth's moon, making the gyroscope more than 90 million times larger than its actual size. Any imperfections on the surface of the gyroscope would be more than 90 million times larger as well. Even at this size, however, with every bump and dip enlarged more than 90 million times, the distance between its high point and low point on the surface would be little more than two feet! From Earth, the "gyroscope moon' would look like a perfect craterless orb in the sky.

Finally, the gyroscope is freed from any bearings or supports by levitating within a fused quartz housing. Six electrodes evenly spaced around the interior of the housing keep the gyroscope floating in the center. A stream of helium gas blows on the gyroscope for about 90 minutes to spin it up to 4,000 rpm.

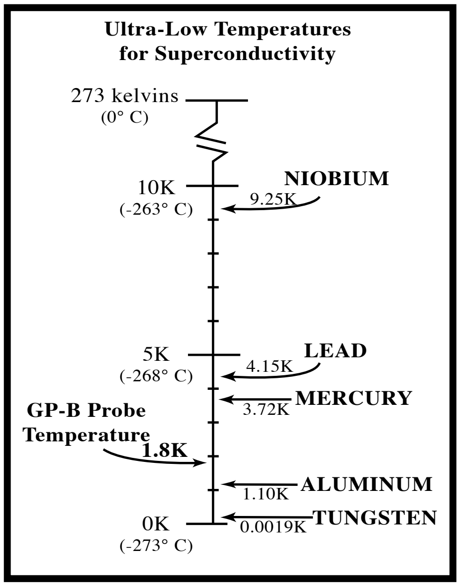
After that, the gyroscope spins in a vacuum, a mere 33 micrometers (one thousandth of an inch) from the housing walls, free from any interfering supports. This space is less than the diameter of a grain of sand (~200 micrometers) or the thickness of a piece of paper (~100 micrometers) and just barely more than the thickness of a sheet of aluminum foil (~12 micrometers)!

B. Superconductivity, the London Moment and the SQUID: Reading the Unreadable

The Gravity Probe B gyroscope is nearly perfectly spherical and nearly perfectly homogenous. While this ensures that the gyroscope will spin with near-perfect stability, its "near-perfect-ness" creates a daunting challenge -- GP-B scientists cannot mark the gyroscope to see exactly which direction its spin axis is pointing.

The "spin axis" is a line running through the two poles of the spinning gyroscope, much like the spin axis of the Earth which runs through the North and South Poles. The spin axis tells scientists which direction a spinning sphere is pointing. GP-B must monitor the gyroscope's spin axis continuously throughout the 1-2 year mission. The problem with GP-B's near-perfect gyroscope is that its surface cannot be marked in any way, so the spin axis is invisible.

For GP-B to "see" the shape and motion of local spacetime accurately, the scientists must be able to monitor the spin axis orientation to within 0.5 milliarcseconds, and spot the poles of the gyroscope to within one-billionth of an inch!

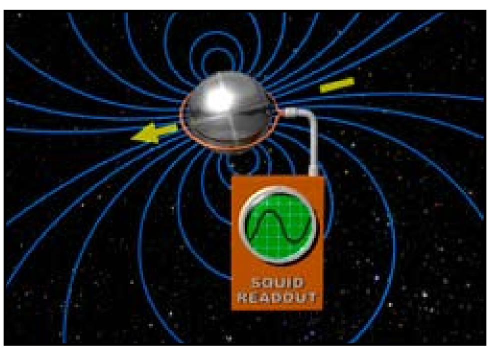


How can one monitor the spin axis orientation of this near-perfect gyroscope without a physical marker showing where the spin axis is on the gyroscope? What tool could sense its orientation without disturbing its rotation? The answer comes from a unique quantum-mechanical phenomenon called the "London moment".

Fritz London, a physical scientist, was experimenting in the early 1900's with metals with a unique property called "superconductivity". This is a property of only some metals and alloys in which the metal (or alloy) conducts electricity without any resistance. When electricity flows through metals, such as copper wires, at room temperature, there is always some resistance to the electrons flowing through the metal. Yet, some metals can conduct electricity without any resistance, and are called "superconducting metals." Pure metals must be dramatically cooled, reducing their temperature to just a few degrees above absolute zero (0 kelvin = -273˚C or -549˚F), for this property to emerge, while certain alloys become superconductive at moderately cool temperatures.

London discovered something remarkable about these superconducting metals; he discovered that when a superconducting metal sphere spins (or a sphere coated with a superconducting metal spins), it creates a magnetic field around itself.

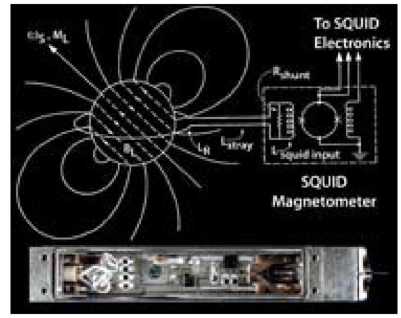
On the surface of the spinning metal, electrons lag behind the metal's positively-charged atoms creating a small difference field. This difference generates a magnetic field. What is even more remarkable about this phenomenon (and fortunate for Gravity Probe B) is that the axis of this magnetic field *lines up exactly* with the physical axis of the spinning metal.



Here was the "marker" Gravity Probe B needed. GP-B scientists coated each quartz gyroscope with a sliver-thin layer of a superconducting metal, called niobium (1270 nanometers thick). When each niobium-coated gyroscope rotates, a small magnetic field surrounds each gyroscope. As Fritz London discovered, the axis of each magnetic field aligned itself perfectly with the spin axis of each spinning gyroscope. By monitoring the axis of the magnetic field, Gravity Probe B knows precisely which direction the gyroscope's spin axis is pointing.

The Gravity Probe B gyroscopes are each coated with niobium, a superconducting metal. When rotating, the niobium layer generates a magnetic field which aligns exactly with the gyroscope's spin axis. A SQUID monitors the magnetic field's orientation with a metal loop surrounding the gyroscope, which tells the GP-B scientists exactly which direction the gyroscope is pointing to within 0.5 milliarcseconds.

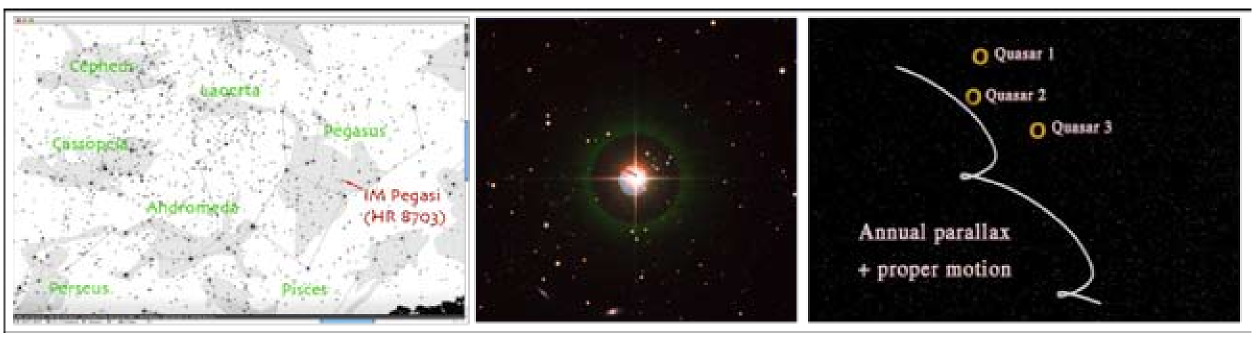
The magnetic field axis is monitored with a special device called a SQUID (Superconducting QUantum Interference Device). The SQUID, about the size of stick of gum, is outside the gyroscope housing and is connected to a superconducting loop embedded within the quartz housing. When the gyroscope tilts, the London moment magnetic field tilts with it, passing through the superconducting loop. The SQUID detects this change in magnetic field orientation. The SQUID is so sensitive that a field change of 5 x 10^{-14} gauss (1/10,000,000,000,000 of the Earth's magnetic field), corresponding to a gyro tilt of 0.1 milliarcsecond, is detectable within a few days.



Using the London moment to monitor the gyroscope's orientation is the one readout scheme perfect for Gravity Probe B: extremely sensitive, extremely stable, applicable to a perfect sphere, and—most importantly—exerts a negligable torque on the gyroscope.

C. The Telescope: Following The Guide Star

During this mission, GP-B predicts that the spin axis of each gyroscope will move with the curvature and twist of local spacetime. The only way we can see this motion is by comparing each spin axis to a fixed line of reference. In this mission, the fixed reference line is the line between the telescope and our guide star, IM Pegasi. The telescope must remain fixed on the exact center of the guide star (within one milliarcsecond, or 1 millionth of an inch) throughout the mission or GP-B will lose its single critical reference line. IM Pegasi was chosen as the guide star because it shines brightly enough and is located in the correct position for traking by the on-board telescope, emits radio waves that can be tracked on Earth, and is visually located a fraction of a degree from a reference quasar.



The Wandering Star

Focusing on the exact center of a star would not be so hard if stars were fixed points of sharp light as they appear to be to the naked eye. However, IM Pegasi, like most stars, wanders across our sky, following a spiraling pattern instead of a linear path, and its light diffracts, or spreads out, as it travels across the universe to our telescope. The wandering motion of the star around the sky is monitored by a sophisticated system of radio telescopes operating in conjunction with each other, called the Very Long Base Interferometer (VLBI). Telescopes from New Mexico to Australia to Germany focus on our guide star and map its movements as

IM PEGASI (HR8703) FACTS

IM Pegasi means "of or in Pegasus", which is a constellation easily seen high overhead on autumn evenings throughout North America, Europe, and Asia. The guide star is actually part of a ***binary star system***, like 46% of the stars in our universe. The binary star system consists of two stars closely orbiting each other. In the case of IM Pegasi, a smaller star orbits the larger star that GP-B focuses on. The smaller star draws the larger star from side to side perceptibly while it orbits. This is another motion that GP-B must account for when focusing on the exact center of the larger star.

Distance - ~300 light years

Right Ascension - 22.50'34.4" Magnitude max. - 5.85

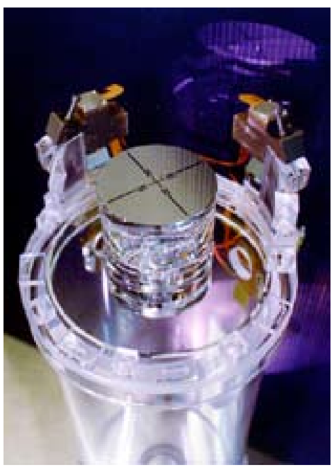
Declination - 16.34'32" Magnitude min. - 5.6

if one telescope dish the size of the Earth was focused on the star. The motions of the guide star are compared to a distant quasar. Quasars are extremely large masses that reside at the edge of the universe, far beyond the guide star. Because of their distance and size, they appear exceptionally still relative to the other stars in the sky, and provide a valuable reference point for VLBI to track the wandering guide star.

Diffracted Starlight

Diffraction occurs when the photons in a light ray spread out while travelling across space. The light from IM Pegasi spreads out to a diameter of 1,400 milliarcseconds, corresponding to an image 0.001 inch across. GP-B must find the exact center of the guide star to within one milliarcsecond, or 0.000001 inches. GP-B scientists resolve this issue in two ways: build an incredibly stable telescope that is free from the smallest amount of gravitational sag, and send the starlight through a super-sensitive palm-sized Image Divider Assembly (IDA) within the telescope.

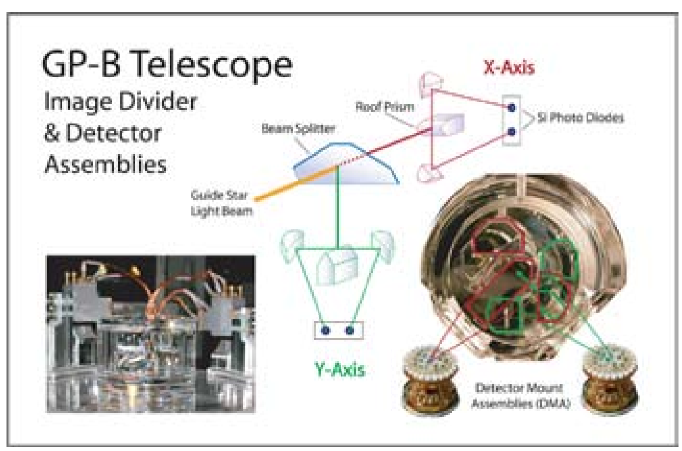
The Telescope



The telescope itself is a 14-inch block of pure fused quartz, identical to the pure fused quartz used for the gyroscopes. Its mirrors are exquisitely polished and its components are connected through a process called “molecular adhesion”. In this process, the surface of each component is polished so smoothly that the molecules of each surface “attach” to each other using the same electrical attraction that occurs on a molecular level.

Most telescopes are capable of finding the exact center of a star by focusing the starlight on a single sensor. The sensor reads how much light is hitting each half of it. The telescope’s alignment is adjusted until each half of the sensor is receiving exactly half of the incoming starlight.

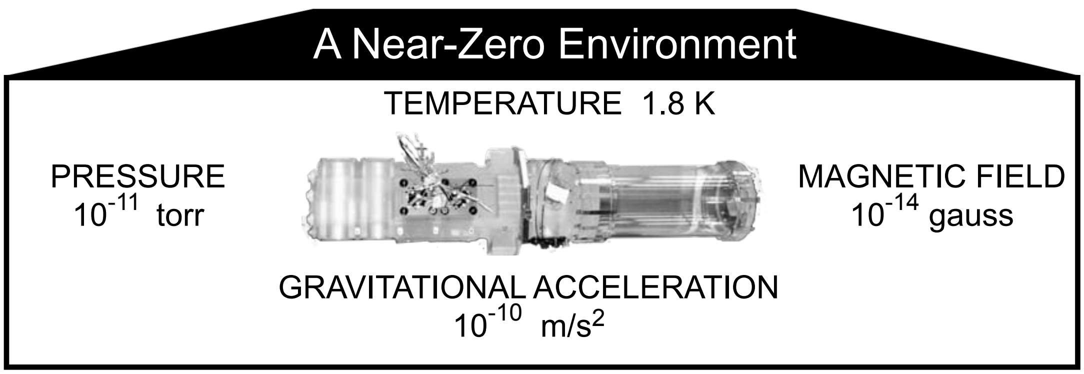
Unfortunately, this method is not precise enough for GP-B. No single sensor is small enough or sensitive enough to split the tiny amount of starlight with which GP-B is working, and aim the telescope within one milliarcsecond. So GP-B created an Image Divider Assembly (IDA), placed on the end of the telescope. The starlight enters the IDA after being focused by three mirrors in the quartz block telescope. The beam is first divided by a beam-splitter, deflecting one half of the starlight, and allowing the other half to continue straight through. The deflected beam aligns the telescope along the y-axis. The continuing beam aligns the telescope along the x-axis.



Each beam then hits a roof-prism (a prism with a peaked edge pointed toward the light), which slices the image in two. Each part of the sliced image is directed toward its own sensor on the Detector Package Assembly (smaller than a dime) and the electrical readouts are compared. When the telescope is pointed exactly at the center of the star (to within one milliarcsecond), the electrical flux (amount of signal) from each sensor will be identical. If they are not identical, the satellite turns the telescope to adjust its aim so when the starlight strikes the roof-prism, exactly half of the beam will hit each sensor.

D. The Force-Free Environment

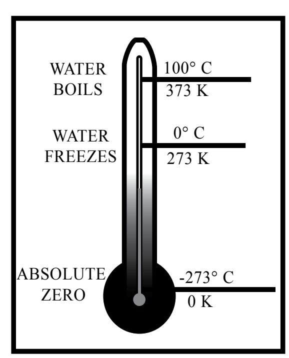
The Gravity Probe B science instrument (four gyroscopes in housings, sitting in a fused quartz block molded to the fused quartz telescope) is designed to make incredibly-precise measurements of the shape and behavior of local spacetime around Earth. However, this instrument will operate properly only if protected from any external forces. The slightest amount of heat or pressure, the influence of a magnetic field, any kind of gravitational acceleration, or the tiniest amount of atmospheric turbulence will destroy the accuracy of the instrument. For Gravity Probe B to succeed, the instrument must be placed in a near-zero environment.



1. Near-Zero Temperature: Near Absolute Zero

Gravity Probe B requires a supercooled environment for two reasons. First, all the fused quartz components (gyroscopes, housings, telescope) must be kept constantly cool to increase their molecular stability. Changes in temperature could cause the components to expand, and expand differentially. The gyroscopes could become unbalanced, the telescope could become misaligned or out-of-focus, or the entire science instrument could warp.

Second, Gravity Probe B depends upon the London moment phenomenon to monitor the orientation of the gyroscopes. The London moment works only with a superconducting metal. Pure metals, like niobium and lead, become superconductive only when they are supercooled, in the neighborhood of absolute zero (0 K, -273° C). Therefore, the niobium coating on the gyroscope must remain supercooled to produce the London moment.



To ensure that the fused quartz components are stable and that the London moment is generated, the GP-B science instrument will be cooled to near absolute zero: 1.8 K or 271.2° C below zero.

The probe rests inside a 645-gallon, 9-foot tall dewar filled with liquid helium.

How does Gravity Probe B create a supercooled environment, and keep it that way for at least twelve months? Creating a supercooled environment in a satellite in space is not that difficult, given how cold space is to begin with. The average temperature of space is calculated to be about 2.76 K, so space provides its own refrigeration.

However, *keeping* that satellite environment supercooled *for an extended time* is a major challenge. The GP-B satellite may be supercooled when it is in the Earth's shadow on the far side of the Earth from the Sun, but every time it orbits into the Sun's light its temperature will rise dramatically. The temperature fluctuations from one side of the Earth to the other are unacceptable for GP-B's science instrument to operate properly.

To maintain its supercooled environment of 1.8 K, Gravity Probe B designed a special dewar (or "Thermos") in which the science instrument rests. The dewar stands nine feet high and surrounds the science instrument with 645 gallons of liquid helium. (Helium gas becomes a liquid at temperatures below 4.2 K.)

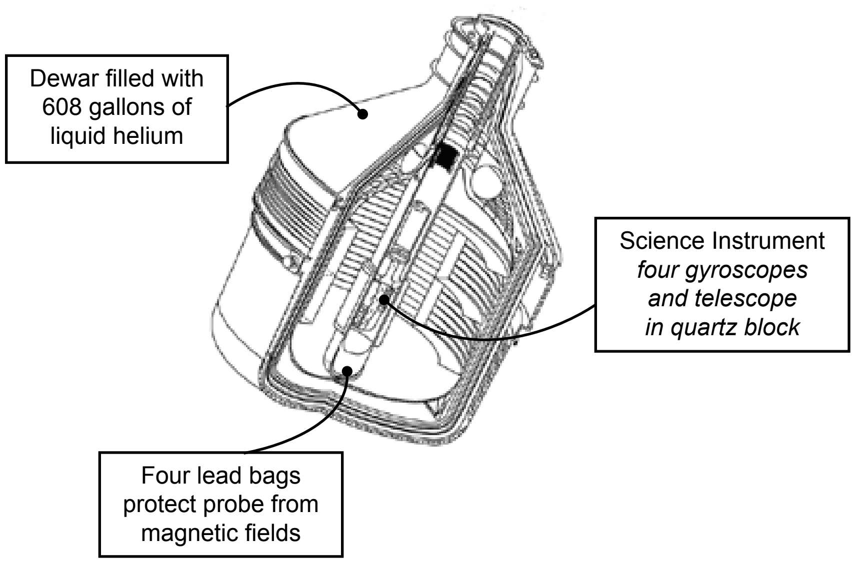
The dewar has several systems designed to limit any changes in the temperature of the liquid helium or the science instrument, including multilayer insulation (multiple reflective surfaces in the vacuum space to cut down radiation from the Sun), vapor-cooled shields (metal barriers, suitably spaced, cooled by the escaping helium gas), and Passive Orbital Disconnect Struts (PODS) (rigid launch supports, invented by Lockheed, which on orbit give looser support with less heat flow).

Despite the efforts of these systems, the liquid helium will slowly, yet inevitably, heat up and boil. As some of the liquid helium changes to gas, the (relatively) hotter gas will further heat up the remaining liquid. Liquid helium will then change to helium gas faster and faster, shortening the time that the GP-B science instrument will be accurate.

To slow down this heating process, a “porous” plug was invented at Stanford and engineered for space by NASA Marshall Space Flight Center and the Jet Propulsion Lab (JPL). The porous plug allows the helium gas to escape while locking the liquid helium inside, reducing the liquid’s exposure to the (relatively) hotter gas, keeping the remaining liquid cooled longer. With the porous plug, the dewar temperature remains more uniform, instabilities from bubbles and “bump-boiling” vanish, and the helium lasts longer. The Gravity Probe B dewar will create a supercooled environment for a longer period than any other space satellite ever has.

2. Near-Zero Pressure, Near-Zero Magnetic Field

Inside the dewar, two other systems help create a near-zero environment for the science instrument.



The “pressure evacuation” system allows the gyroscopes to spin in a near-perfect vacuum, ensuring that friction from the air is non-existent. The gyroscopes spin at 4,000 rpm, a mere 33 micrometers from the interior sides of each housing. After launch, each housing is evacuated to less than 10^{-11} torr.

The “lead bags” system protects the gyroscopes and the London moment from magnetic field interference. Within the dewar, four superconductive lead “bags” surround the science instrument. One at a time, each lead bag was placed inside the next one and expanded gradually. By expanding the bags and using four layers of lead protection, the possible magnetic field interference has been reduced to less than 10^{-14} gauss.

3. Near-Zero Acceleration: A Precise Orbit

It may appear that the satellite *is carrying* the gyroscopes around the Earth in a polar orbit. In fact, one of the gyroscopes is in a *free-fall orbit around the Earth*. This gyroscope acts as a "proof mass", laying out a near-perfect gravitational orbit. The satellite actually follows the orbital path of this gyroscope, and faces the difficult challenge of encasing this free-falling gyroscope without interfering with or touching it. Given that the gyroscope spins a mere 33 µm from the edge of its housing, the satellite has very little margin for error.

For the most part, the satellite stays on course by following the same free-falling orbit. However, outside the satellite, two factors can alter the satellite's path. The solar radiation streaming from the Sun is enough to knock the satellite askew, and friction from atmospheric gases can slow the satellite down.

GP-B needs extremely sensitive thrusters to re-orient the satellite and keep it on its proper path. Here's where the escaping helium gas that slowly boils off from the liquid helium comes in handy. Minute amounts of gas, $^1/_{10}$th of a human breath or a few millinewtons of force, provide just the right amount of thrust necessary to adjust the satellite's position. The thrust force of the escaping helium gas provides plenty of force to keep the GP-B satellite in its precise position (within 10 milliarcseconds of a perfect Earth orbit, pointing to within 1 milliarcsecond of the exact center of the guide star).

WHY LOW ORBIT?

Why does the GP-B satellite orbit so close to the Earth's atmosphere? Even at the edge of the Earth's atmosphere, the individual molecules and atoms of the atmosphere create too much friction for the satellite to follow its precise orbit. Why not orbit farther from Earth, outside its atmosphere?

The reason is that the effects of local spacetime (its curve and twist) weaken dramatically as one moves farther from the Earth. GP-B chose an orbit that would get it as close to the Earth as possible, to see the spacetime effects more clearly. A 400-mile altitude was the closest GP-B could get with a tolerable amount of atmospheric friction.

Concluding Questions

Gravity Probe B is one of the most sophisticated physical experiments ever attempted. It has been in design for four decades and combines the efforts of dozens of scientists and engineers at Stanford University, Lockheed Martin Aerospace, NASA's Marshall Space Flight Center and VLBI scientists, along many others. It has spawned numerous advances in navigation technology and materials precision. Most importantly, it will give us all a glimpse into two fundamental questions about the sublime structure of our universe.

1) Will Gravity Probe B prove or disprove Einstein?

Will the results of Gravity Probe B verify Einstein's theory of curved spacetime and frame-dragging, or will Einstein's theory be refuted? If the former proves true, then we will have confirmed to a new standard of precision the mathematics of Einstein's Theory of General Relativity. If the latter proves true, then we may be faced with the challenge of constructing a whole new theory of the motion of matter.

2) Will Gravity Probe B prove or disprove "Mach's Principle"?

"Mach's Principle" is the idea, first stated clearly by Ernst Mach in 1883, that when one describes motion the concept is meaningless unless that motion is occuring relative to something else. In other words, if there were no universe around you, you would not be able to move because there would be no background against which you could measure your movement.

Newton's theory of gravity contains no place for Mach's Principle. In his theory, motion is perfectly well-defined even if there were no other matter because the background of space is absolute. All motion occurs relative to absolute space.

Einstein, like Mach, hoped to do away with the concept of "absolute space," and many physicists believe that he was partially successful. Just how fully Einstein's General Relativity incorporates Mach's Principle is still a matter of lively debate. But recent calculations by Dieter Brill and Jeffrey Cohen strongly suggest that, within Einstein's theory, our local frame of reference is in fact physically tied to (or "dragged" by) the contents of the rest of the universe.

Gravity Probe B will shed the first experimental light on this issue, which is one of the most fundamental and fascinating questions in science. If GP-B does indeed detect frame-dragging caused by the Earth, this will go a long way toward vindicating the intuition of relativists like Mach and Einstein. If frame dragging is not observed, or is observed to a degree different than is predicted by General Relativity, this will propel the debate about the origin of our sense of inertia and the nature of space and time.

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"**Around-the World Atomic Clocks: Predicted Relativistic Time Gains**" and "**Around-the-World Atomic Clocks: Observed Relativistic Time Gains**" by J.C. Hafele and Richard Keating. Science Magazine, vol.177, pgs.166-170, July 1972.

CLASSROOM CONNECTIONS

1. "Seeing" Newton's Gravity

In this activity, students observe the effect of a magnet on a ball bearing and connect it with a central assumption of Newton's gravity -- that it transmits instantly across empty space.

2. The Equivalence Principle

Students engage in four activities to explore the relationship between mass, acceleration while falling, and force. These activities raise the question of whether gravity is actually a force.

3. The Speed of Gravity?

Exactly how fast does the force of gravity transmit? In this exercise, students calculate how much time it takes the Sun's gravity to cross the solar system and reach the planets.

4. Models of Spacetime

This activity has two parts. The first part provides instructions for constructing a large-scale model of curved spacetime for use in the classroom. The second part provides demonstrations and questions that engage the model with your students.

5. Frame-Dragging of Local Spacetime

With this simple model, students can see the theoretical idea of frame-dragging as scientists conceive of it, and see how the spinning Earth can affect nearby objects in space.

6. The Physics of Gyroscopes

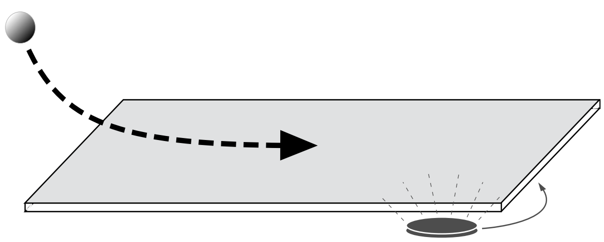
Students engage in four explorations to understand what a gyroscope is, how it works and why it is so useful in both science and technology.

“Seeing” Newton’s Gravity With Marbles

SUBJECT: **Observing Newton’s Theory of Gravity**

Introduction: According to Newton’s theory of gravity, all bodies possess the force of attraction called “gravity”. Larger masses, such as the Sun, attract smaller masses, such as the planets and comets, more strongly, causing the smaller masses to move toward the larger masses. In our solar system, the planets orbit the Sun due to the force of the Sun’s gravity pulling them into this elliptical path. Comets soaring through the galaxy are curved toward the Sun due to gravity’s pull. In this demonstration, we use the force of magnetism to model how the force of gravity reaches out and pulls comets toward the Sun and how planets stay in orbit.

MATERIALS
- Flat Magnet (the stronger the better)
- Steel Ball bearing (at least 8mm)
- Large piece of cardstock (~ 1ft. x 3ft.)



Setup: Place cardstock on table or floor. Place magnet underneath one end of the cardstock. Draw a circle around the magnet about 1cm larger than the magnet.

Procedure: Roll a steel ball bearing down the length of the cardstock. Try to roll it near the hidden magnet. Observe what happens to the path of the ball bearing when it comes close enough to the magnet to react to its magnetic field. Can you make the ball bearing turn 45 degrees? 90 degrees? 180 degrees? 360 degrees? Try to roll the ball bearing at the right speed and distance from the magnet so it curls around it and comes back to you. This may take many efforts.

Observations:

1. What happens to the ball bearing when it...
   …Rolls near the magnet?
   …Rolls far from the magnet?
   …Rolls fast?
   …Rolls slow?

2. How should you roll the ball bearing to make it curl around the magnet? What speed, starting distance, path, or direction?

("Seeing" Newton's Gravity Cont.)

Connection Questions

1. What does the ball bearing represent? What does the magnet represent? What does the magnetic field represent?

2. How does the ball bearing "know" that the magnet is there? How does it "feel" the magnet's pull?

3. In what way is this model NOT an accurate demonstration of Newton's gravity?

4. How fast does the magnetic force travel from the magnet to the ball bearing? Does the ball bearing feel the magnetic force at the same instant it enters the circle?

Summary: The purpose of this activity is to demonstrate how planets orbit the Sun according to Newton's theory of gravity. The magnet represents the Sun; its magnetic field represents the Sun's gravitational field. The ball bearing represents a planet moving near the Sun. It is a real challenge to get the ball bearing to bend around the magnet; it requires a specific speed and placement, as it does for a planet to go in orbit around the Sun. Most masses moving through our solar system either pass on through or fall into the Sun.

The critical piece to understand from this demonstration is that Newton believed that planets respond to an invisible force called 'gravity'. They react in a manner similar to how metal balls react to magnets. The questions this should raise are: How does a planet "feel" the Sun's gravity? How does the planet know that the Sun is there? Additionally, how does the Sun's gravity reach out into space? This activity is not designed to answer these questions. Rather, it is designed to uncover assumptions about gravity and raise the questions that Einstein had about gravity.

The Equivalence Principle

SUBJECT: **Four Demonstrations of the Equivalence Principle**

Introduction: According to Newton's theory of gravity, all objects fall to the ground because of the Earth's gravity. The Earth's force of gravity pulls the objects down as soon as they are released or fall off a table. But some interesting results happen when we drop two masses simultaneously. When we compare these results with what happens in outer space, we are introduced to the Equivalence Principle which states that physics in a gravitational field, like here on Earth, are equivalent to physics in an accelerating spaceship. Acceleration due to gravity or due to one's frame of reference accelerating are indistinguishable.

DEMONSTRATION #1 - THOUGHT EXPERIMENT

Procedure: Imagine you and a friend are each pushing identical wagons across a building roof. Your friend's wagon is empty while your wagon is filled with cement. You start pushing them at the same time and you push them at the same rate across the roof. You both reach the edge of the roof at the same time, and the wagons fall to the ground below.

Observations:

1. Which wagon is heavier?
2. Which wagon takes more force to push across the roof? (Remember, F=ma).
3. When the wagons fall to the ground, which hits the ground first? The heavier one or the lighter one?
4. Did gravity pull on each wagon with the same amount of force?

DEMONSTRATION #2 - BALL DROPS

Setup: 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. Find a partner and take the objects to an empty space where you can drop them safely.

Procedure: Stand on a stepladder or stable, sturdy chair to drop the objects from a high point. (This will give you more time to observe them fall to the ground.) Hold them out at shoulder height and drop each pair simultaneously. Repeat several times with all objects.

Observations:

1. Which objects hit the ground first? The heavier or the lighter? Or do they hit simultaneously?

2. Do the objects fall at the same rate? Why or why not?

(The Equivalence Principle Cont.)

DEMONSTRATION #3 - PENDULUM SWINGS

Setup: Find a place to hang and swing a paper cup. You can attach it to the top of a doorway, to a test tube holder, to the edge of a table, to a basketball backboard, to a pipe, or to a tree limb. Tie a length of fishing line to a paper cup and attach it to the doorway (or whatever you use). Make the cup hang as low as possible without hitting the ground. Then attach a second cup. Make sure it is the exact same length. Now collect materials of different mass that you can put in each cup (e.g., sand, popcorn, dirt, rocks, paper, peanuts, cooked beans, raw beans, etc.)

Procedure: Fill each cup with materials of different masses, so that one cup is significantly heavier than the other (make sure not to overfill the cup to the point that the fishing line detaches). Slowly swing the two cups back and forth until the fishing line is nearly horizontal. Do not go any higher if the materials start to fall out. Release the cups simultaneously. Observe which cup reaches the bottom of the arc first. Repeat several times with different materials.

Observations:

1. Which cup reaches the bottom of the arc first? The heavier or the lighter? Or do they reach it simultaneously?

2. Do the cups fall at the same rate? Why or why not?

Summary A: From these demonstrations, you should see that all objects fall to the ground at the same rate, 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. This often appears true in our experience because air resistance tends to slow the fall of lighter objects more than heavier objects, making heavier objects appear to fall faster.

Einstein was puzzled by this “simultaneous acceleration” principle because it meant that somehow gravity, which caused the objects to fall, must be pulling on each object with a different amount of force. (Heavier objects require more force to accelerate because they have more inertia.) But how could a force, such as gravity, “know” to pull on different size masses with a different amount of force, and pull with the exact amount to make them all fall at the same rate? The amount of gravity around the Earth determined by the mass of the Earth, which does not change significantly. So how could two unequal masses fall at the same rate?

We must take a look at gravity from outer space to understand this phenomenon...

(The Equivalence Principle Cont.)

DEMONSTRATION #4 - SPACESHIP THOUGHT EXPERIMENT

Procedure: Stand on a stepladder or stable, sturdy chair again, as in Demonstration #2. Take just one ball this time. Hold it out at shoulder height and get ready to drop it. But hold on...

Before you drop it, imagine you are floating in a spaceship in outer space, far from any gravitational fields. Imagine that the ball you are holding is actually floating next to you. There is no gravity in outer space, so neither you or the ball fall to the ground.

Now, do two things at the same time. Release the ball, and imagine that your spaceship just accelerated upwards at 9.8 m/s^2. 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.

1. What happens to the ball?

2. Does the motion of the ball look different to you in the spaceship than it does here on Earth?

3. 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 B: What you see in the accelerating spaceship is identical to what you experience here on Earth. This is the Equivalence Principle. Gravity is acceleration; the effects of each are equivalent and indistinguishable. When objects fall here on Earth, they are not being pulled down by the force of gravity. They are simply accelerating at the same rate, without being pulled by any force. Why do they all fall toward the Earth, even from different sides of the Earth, if there is no attractive force? Because, Einstein theorized, spacetime around Earth is warped toward the center of the Earth, and objects “fall” because they are following the structure of spacetime.

The Speed of Gravity?

SUBJECT: **Calculating the speed of gravity and light**

Introduction: According to Newton's theory of gravity, the force of gravity reaches out across empty space instantly. Planets instantly feel the pull of the Sun's gravity. Baseballs instantly feel the pull of the Earth's gravity. However, this idea of a force instantly transmitting across space puzzled Einstein. In his special theory of relativity (1905), Einstein surmised that nothing could travel faster than the speed of light, including any energy or forces. And since light did not transmit instantly across the universe, how could gravity?

Procedure: Do the following calculations to see how long it takes light to travel from the Sun to each of the planets. Fill in the answers on the chart. In the last column, list one or two things that could occur in the time it takes light to travel from the Sun to each planet.

	Distance from Sun - avg. (km)	Speed of Light (km/s)	Time Elapsed (min)	Possible Event
MERCURY	57.9 million	299,792	*3.2*	*phone call*
VENUS	108 million	299,792		
EARTH	150 million	299,792		
MARS	228 million	299,792		
JUPITER	778 million	299,792		
SATURN	1.4 billion	299,792		
URANUS	2.9 billion	299,792		
NEPTUNE	4.5 billion	299,792		
PLUTO	5.9 billion	299,792		

(The Speed of Gravity? Cont.)

Connection Questions

1. Does light travel instantly across the universe? Does light travel instantly across your classroom?

2. How long does it take for light to transmit from the nearest light bulb to this paper? Estimate the distance and calculate.

3. How fast does the magnetic force transmit? How long does it take for a magnet to reach a paper clip 1 cm away from it? Calculate.

4. How fast does the force of gravity transmit? As fast as light? Faster than light? Instantly?

5. Who do you think is right, Newton or Einstein? Does gravity transmit instantly and cause the planets to orbit, or is gravity limited to light speed, meaning something else causes the planets to curve around the Sun? What else could it be?

Summary: Einstein decided that due to this contradiction, and due to the Equivalence Principle, that gravity did not transmit as a force. Instead, the moons orbited planets, comets turned toward the Sun, and objects fell to Earth because the structure of spacetime was curved near masses. The objects themselves were not curving or moving in an elliptical path against the background of space; they were simply following the curves of local spacetime itself.

Spacetime Model

ASSEMBLY -- 15 min.
ONE-TIME PREP -- 1 hr.
COST -- ~$75

Where To Find Materials

PVC ELECTRICAL CONDUIT PIPE

The PVC electrical conduit pipe can be found in a large hardware store, usually sold in 10-foot lengths. It is different than normal PVC pipe because it has a “mouth” at one end. The “mouth” is the right size to fit 1/2” pipe inside it. You will probably have to buy sixteen 10-foot pipes to make sure each section has a “mouth” on it. Cut a 30” section off of each 10-foot pipe. Make sure you cut the end that has the “mouth” on it.

PVC PLUMBING PIPE

The PVC plumbing pipe can be found in a large hardware store, usually sold in 10-foot lengths. You’ll need a power saw to cut it, or get the hardware store to do it for you.

CLAMPS

The clamps are found in the hardware section. You only need 8, not 12. They need to be large enough to fit completely around the pipe and touch on the other side. They grip the spandex.

T-CONNECTORS

These PVC joints are in the plumbing department. They must fit 3/4” pipes.

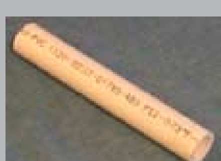
SPANDEX

The spandex can be found at a fabric store or online: http://www.baerfabrics.com/, http://www.spandex.com

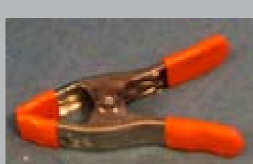
MATERIALS

* Spandex sheet -- 50” x 50”

* PVC T-connectors (16)

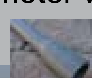


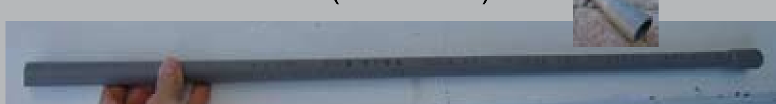
* PVC pipe -- $^3/_4$” diameter
Eight 30” sections (20 ft. total)



* Heavy Duty clamps (8)

* PVC electrical conduit pipe -- $^1/_2$” diameter with “mouth”
Sixteen 30” sections (40 ft. total)



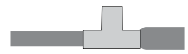


ASSEMBLING THE FRAME

PART A -- MAKE THE CIRCLE

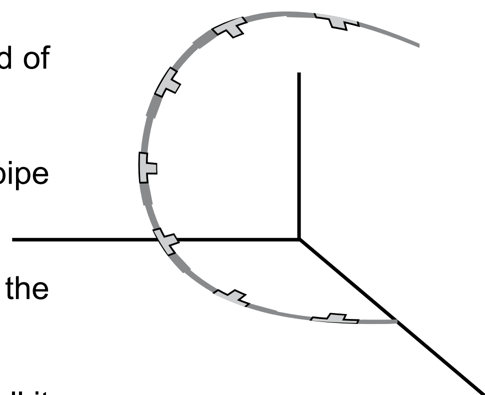
1. Lay out eight (8) sections of the electrical conduit pipe end-to-end.

2. Slide one T-connector onto each section, wedging it against the wide end of the pipe.



3. Slide each section together firmly, putting the pipe in the "mouth" of the next section.

4. You now have a pipe of eight connected sections.

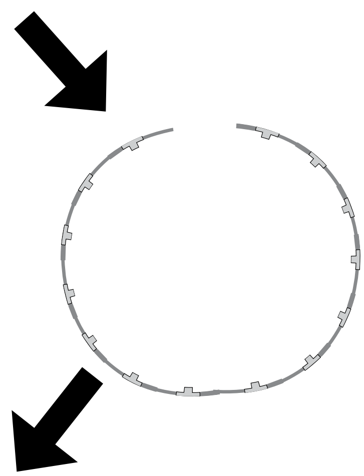


5. Pick up one end of the pipe. Push the other end of the pipe against a wall or into a corner.

6. Slowly curl one end toward the wall, so the pipe forms a "U".

7. Step on the pipe on the floor to stabilize it for the next step.

8. Grab the pipe end that is against the wall and pull it up slowly to meet the other end.

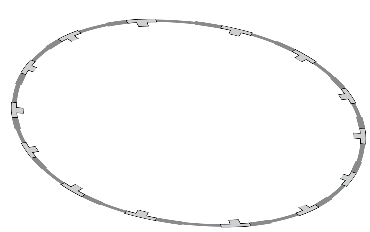


9. While holding each end of the pipe in each hand, move the pipe circle so the gap is in front of your chest and the pipe ends are meeting each other horizontally.

10. Carefully bend the pipe so the ends of the pipe are meeting each other horizontally. Connect the ends.

PART B -- MAKE THE OTHER CIRCLE

1. Repeat all these steps to form the second circle with the electrical conduit pipe.



PART C -- CONNECTING THE CIRCLES

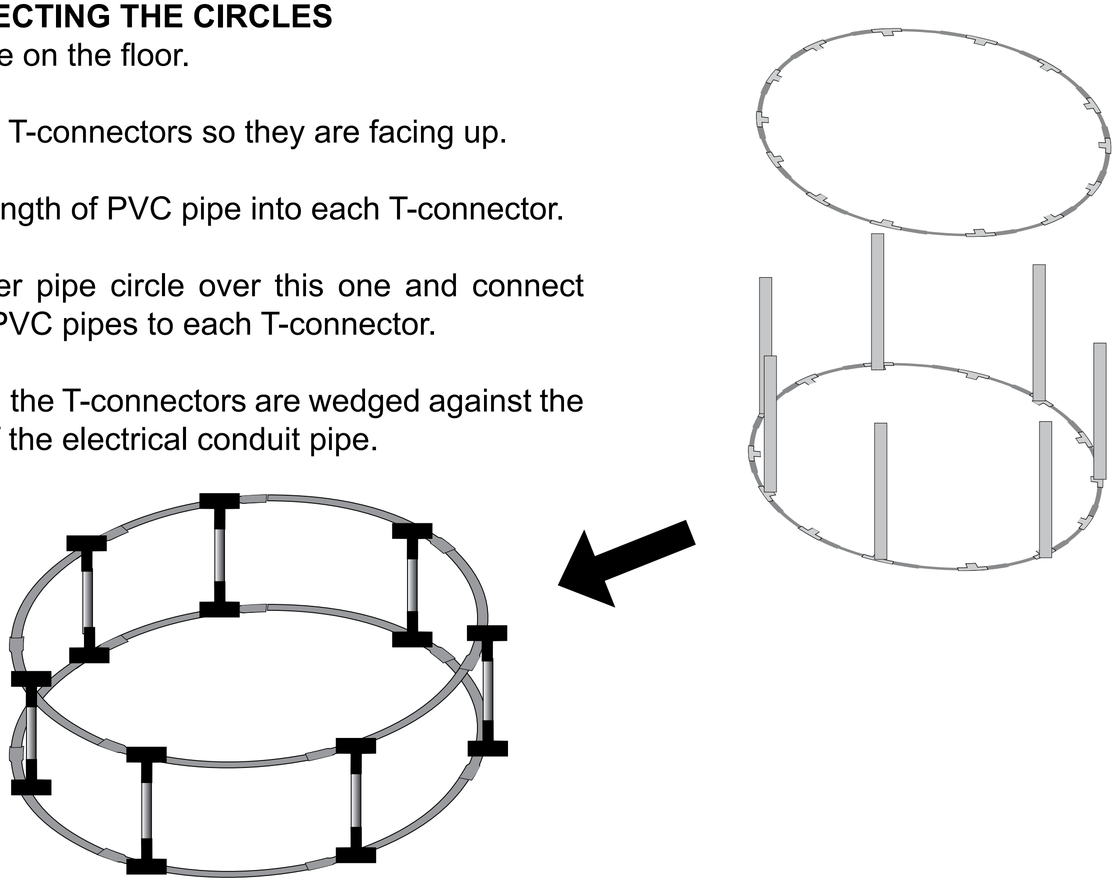
1. Lay one circle on the floor.

2. Turn all eight T-connectors so they are facing up.

3. Slide each length of PVC pipe into each T-connector.

4. Lay the other pipe circle over this one and connect each of the PVC pipes to each T-connector.

5. Make sure all the T-connectors are wedged against the wide ends of the electrical conduit pipe.



PART D -- ATTACH THE SPANDEX

1. Lay out the spandex in the middle of the frame.

2. Grab the spandex in the middle of one of its sides.

3. Wrap a few inches of the fabric around the top pipe.

4. Squeeze the clamp open and slide it over the spandex and the pipe so that it grabs the spandex on the inside of the circle. The clamp should be closed all the way (not squeezing the pipe, just grabbing the spandex).

5. Clamp the spandex on the other side of the circle and repeat until you have placed all eight clamps equidistant around the circle.

6. Walk around the circle and pull the spandex tighter to make sure it is taut across the frame.

ALL DONE!

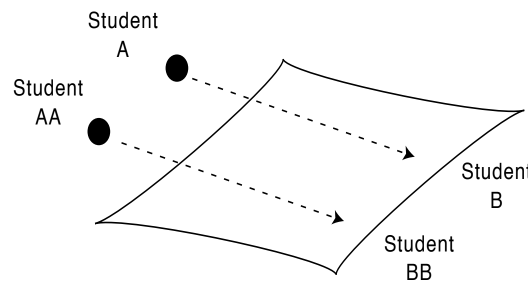
(Spacetime Model Cont.)

***SUBJECT*: A Model of Spacetime**

Introduction: According to Einstein's Theory of General Relativity (1916), motion in the universe is determined by an invisible, intangible structure of spacetime. Near sources of mass-energy (planets, stars, galaxies, black holes), spacetime is curved causing planets and moons to orbit and light to curve. Using a plastic frame and a spandex sheet, you can create a simple model of spacetime. On this model, you can demonstrate several phenomena that are caused by the curvature of spacetime.

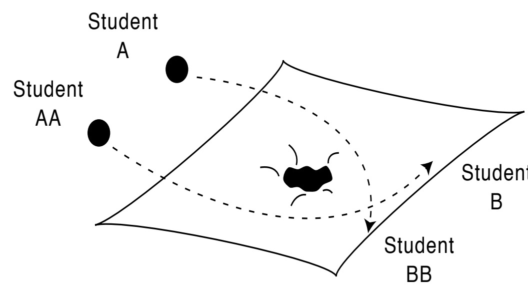
Introductory Model - Flat and Curved Sheet

You can do this model without the frame



1. Hold a spandex sheet flat and taut. Have students stand around the sheet.

2. Roll several small balls back and forth across it. Observe their paths. The balls roll straight across the sheet. If Student A rolls a ball across the sheet toward Student B, the ball rolls straight to Student B - its path does not change.



3. Now place a heavy ball or weight in the center of the bedsheet. Hold the sheet taut, but let it sag in the middle where the weight is.

4. Roll the small balls across the sheet again. Observe their paths. This time, if Student A rolls a ball across the sheet toward Student B, the ball curves away from Student B - its path does change. Try and make the balls curve around the weight in some kind of orbit.

Why do the balls curve around the weight? Because they have no choice! In this model of spacetime, as the balls roll across the sheet, they are "gripped" by the sheet. Whatever shape the sheet takes, the balls will follow. In areas of space where the structure is flat, the balls roll straight. In areas of space near masses, spacetime curves and the balls curve with it.

(Spacetime Model Cont.)

Model 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.

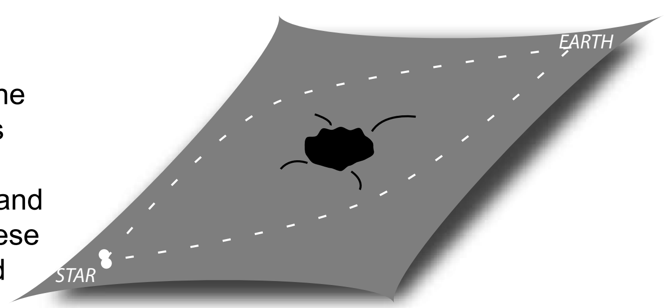
Challenge B – You want to put a satellite into orbit around the "near planet". Work together and figure out how best to put your "satellite" into orbit around the center mass.

Model 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.

(Spacetime Model Cont.)

Challenge 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.

QUESTIONS

Challenges A & B

1. What are three key variables you must control when directing a satellite into an orbit?
2. Why is it impossible for you to put your "satellite" into a perpetual orbit in this model, even thought we do this all the time in space (e.g., the Space Shuttle, communication satellites, GPS satellites)?

Challenges 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 gravity have to do with it?
6. How is this phenomenon similar to what a lens does to light?

Challenge 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 than a neutron star, but the neutron star has slightly more mass. Which creates more spacetime curvature?
9. Do more dense objects always create more curvature than less dense objects? Why or why not?

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.

Frame-Dragging of Local Spacetime

***SUBJECT*: Demonstration of frame-dragging**

Introduction: One of the predictions of Einstein's general theory of relativity is that local spacetime is twisted by the rotation of the Earth. Hans Thirring and Joseph Lense called this "frame-dragging" - any rotating mass will drag the local spacetime frame of reference with it. The predicted drag is very small and fades as one travels farther from the rotating mass, but the twist nearby can affect the paths of light, energy, and other masses.

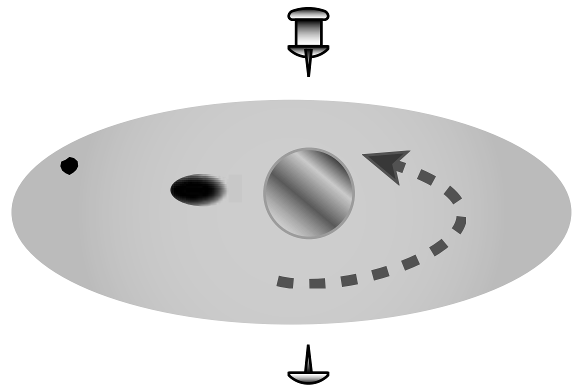
MATERIALS
- Small paper plate (5 - 10")
- Small ball (a superball)
- Honey or molasses
- Peppercorns
- Food coloring
- Thumbtacks (flat head)

Setup: Each group needs a paper plate, honey, a superball, a tack, and some peppercorns.

Procedure:

1. Poke a tack through the center of the plate pointing upwards.

2. Pour a layer of honey on the plate. It should be enough to form a sizeable puddle on the plate that is several times wider than the superball.



2. Place the ball firmly on the tack.

3. Place a peppercorn in the honey, near the edge of the plate.

4. Squeeze a drop of food coloring in the honey around the ball. (Note: don't put the food coloring in the honey until you are ready to start twisting, as it will diffuse through the honey quickly.)

5. Twist the superball at different speeds while keeping it in the middle of the plate. Continue for several minutes.

6. Observe the effects of the twisting ball.

Observations:

1. What happens to the honey? To each of the peppercorns?
2. How does the honey react differently near the ball than far from the ball?
3. What happens when you twist the ball at different speeds? How does the honey react differently?

(Frame-Dragging Cont.)

Connection Questions

1. What did the parts of the model represent? The ball? The honey? The peppercorns? The food coloring?
2. What is the “local spacetime frame” in the demonstration?
3. Where does the “frame-dragging” occur in the demonstration?
4. What causes the “dragging” in the model?
5. Why do each of the peppercorns react differently to the twisting ball?

Summary:

The purpose of this activity is to demonstrate how the Earth twists the local spacetime frame, but does not affect a distant spacetime frame. The ball represents the Earth, the honey represents spacetime, and the peppercorns represent other masses (stars, planets, etc.) in the spacetime frame at various distances. The food coloring is used to highlight the honey’s motion, and does not represent an astronomical object.

A major limitation of this model is that the Earth spins much faster than you can twist the ball (~1,000 mph), and the spacetime frame spins much, much slower (~0.000000001 mph) relative to the Earth’s rotation than the honey moves relative to the ball’s rotation.

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. It is unclear to scientists exactly how this phenomena occurs. The theory of general relativity suggests that spacetime and masses have a mysterious mutual “grip” on each other.

The Physics of Gyroscopes

Introduction

The gyroscope is the central component to the Gravity Probe B experiment. The entire probe and satellite are built to surround and support GP-B's ultra-spherical 1.5-inch gyroscope. The beauty of the gyroscope is that it maintains its orientation in space while it is spinning. Because of this property, gyroscopes are used to navigate ships, planes, missiles and satellites.

Key Principle

A spinning object will maintain its angular momentum as long as no external forces interfere with its motion. This property is called rotational inertia.

Explorations

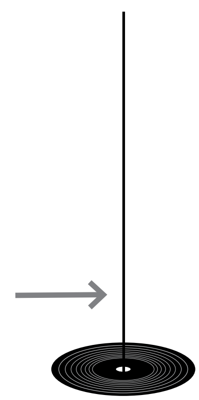
A. Swinging Record

Equipment: 5-ft string, record, crayon/pencil

1) Tie string to crayon.
2) Slip record over loose end of string and hang record down over crayon. The record should be hanging horizontally (parallel to the ground), more or less.

Test A: Set record swinging gently by pushing the string near the record. Does the record stay horizontal? How far does it vary from horizontal? Does it matter how hard it is swinging?

Test B: Repeat the first test, but first give the record a sharp spin. Make sure when you spin it that you thrust it along the horizontal, so that the record starts out in a horizontal position before you start swinging the string. Does the record stay horizontal? How far does it vary from horizontal? Does it matter how hard it is swinging?



B. Tilting Wheel

Equipment: bike wheel (large and light the best) with stunt peg/handles attached to axle (bike shop can do this)

1) Hold the wheel vertically out in front of you with one hand on each side of the axle. Make sure the wheel is not touching your body or your arms.
2) Turn it toward the ground (toward horizontal) to the right and the left.

Questions -- Do you notice any pulling on the wheel when you turn it? In which direction do you feel the pull?

C. Hanging Wheel

Equipment: rope with handle and hook, bike wheel, partner to hold rope, chair to stand on

1) Attach rope hook to wheel axle.
2) Have partner stand on chair and hold rope high.
3) Turn wheel to a vertical position (axle is horizontal, held by rope and your hand).
4) Release wheel and observe.

(Gyro Physics Cont.)

5) Return wheel to vertical position and spin it rapidly.
6) Release it again and observe.

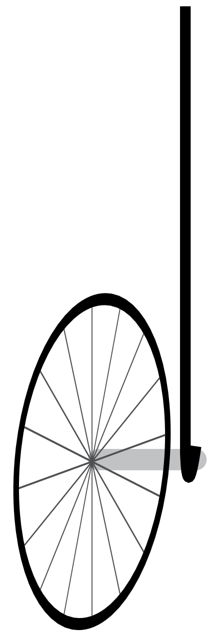
Questions -- What happened to the spinning wheel when you released it? Which direction did it turn? What happens if you spin the wheel in the other direction?

D. Send Yourself Spinning

Equipment: bike wheel, office chair

1) Sit on office chair. Make sure you are well-balanced. Pull feet up so if the chair turns your feet will not hit anything.
2) Hold the wheel vertically out in front of you with one hand on each side of the axle. Make sure the wheel is not touching your body or your arms.
3) Turn it toward the ground (toward horizontal) to the right and the left.

Questions -- What happens when you turn the wheel? Why does the chair move?



The GP-B gyroscope is designed to measure a very miniscule change in the orientation of spacetime around Earth during the course of one year in orbit. Since gyroscopes maintain their orientation in space while they are spinning, the only reason that the GP-B gyroscope will shift its orientation is if spacetime itself is turning. The simple gyroscope will allow GP-B scientists to “see” our invisible, intangible spacetime.

(These explorations were adapted from an article originally published in The Technology Teacher, October 2002 by the International Technology Education Association.)