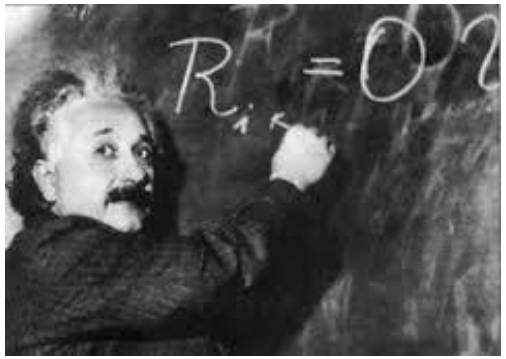
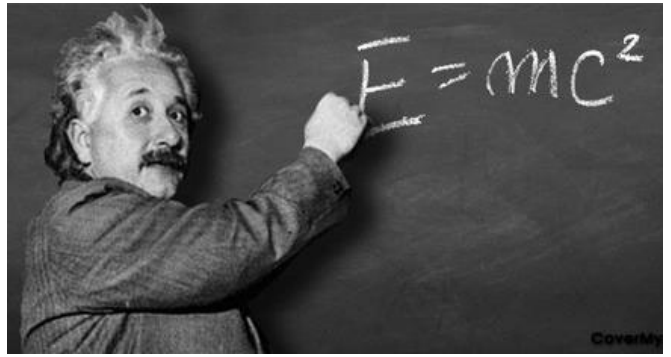
Lecture 5





Einstein's General Relativity Application

The Nobel Prize 2001 Carl E. Wieman

During high school I was a good student, but never quite at the top of the class. I mastered the material, but was usually a little too independent to do precisely what the teacher wanted, and so was never considered among the very best students. Usually the worse the teacher (at least according to me), the lower was my standing. Although always interested in science, my most memorable classes were in literature and writing.

As one might imagine, going from the woods of Oregon to MIT was quite a culture shock. I did not do particularly well in classes my freshman year, but I greatly enjoyed an informal freshman seminar on ...

2 Nobel Winners

British biologist Richard Roberts failed his first attempt at A level physics. American mathematician Stephen Smale failed physics in university. Yet both bounced back, made dramatic discoveries and went on to carve out illustrious academic careers

"The Sunday Times", Think, 1st Feb. 2015

Rhea Khanna

The Nobel Prize 2003 (Medical Physics)

Back in London after the war I was hurriedly told by my school master that I should take the 11+ examination … I took the exam and failed, but not completely. The mark I received was not quite high enough to get me into the local Grammar school … I left school at age 15 and started work as a printer's assistant … was called up for National Service to serve in the army for two years, returning to Westcott after National Service in 1954. I studied for Advanced Levels part time for approximately two years and gained University entrance.

Sir Peter Mansfield

What is Passion ?

No one could earn a PhD unless he had suffered in the process.

Arlow Shapley, Harvard, 1925

The plight of a suffering graduate student is perhaps best expressed by a line from poet Percy Byshe Shelley 1819 : “Like the poets, they learn through their suffering what they teach in their songs”

Passion (from the ***Latin*** verb *patere*) meaning … … to suffer

A Harvard study : https://www.inc.com/jessica-stillman/new-harvard-research-to-be-successful-chase-your-purpose-not-your-passion.html and https://www.youtube.com/watch?v=CVEuPmVAb8o

A little Revision with Comparisons

Special Relativity Reminders : 2 axioms !

1) The laws of physics are the same.

2) The velocity of light in vacuo is the same.

Sander Bais

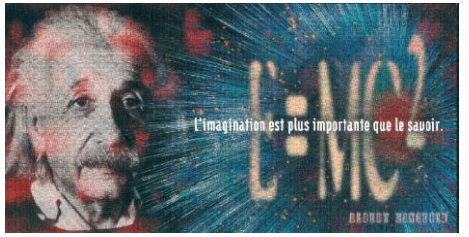
Some books :

1) Principle of Relativity (Newton's 1st Law)

2) Principle of the constancy of the speed of light

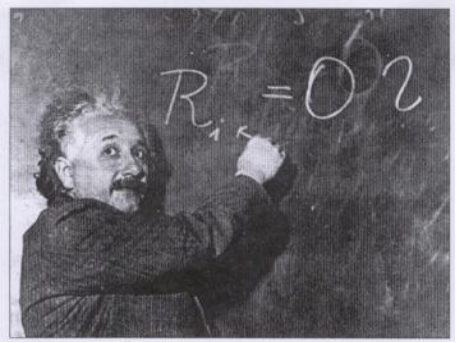
Einstein's "two" Relativities

Special Relativity (SR) deals with uniformly (constant speed) moving inertial reference frames … not accelerating.



i.e. effects of rest and constant speed movement cannot be distinguished.

General Relativity (GR) incorporates accelerating frames.



i.e. effects of acceleration and gravitation cannot be distinguished.

Einstein's "two" Relativities

Special Relativity : no mechanical, electrical, optical or any other physical measurement, one may perform inside an enclosed frame moving smoothly along a straight track … no easy detection of rest or moving frame.

General Relativity : uniform motion would give way to accelerated motion, which would be easily noticed.

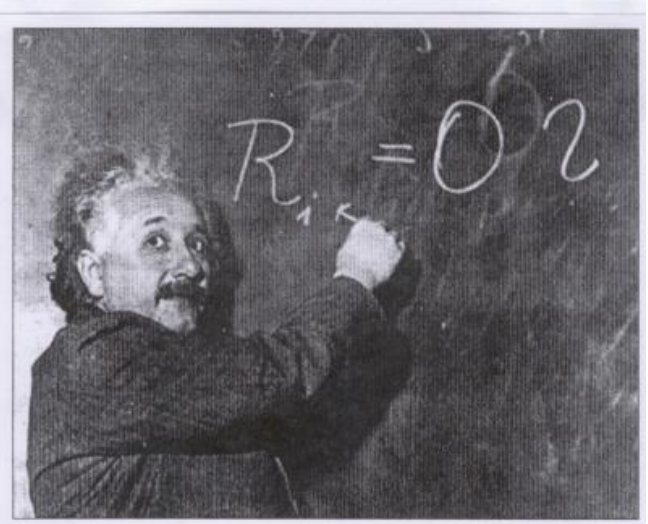


Fig. 1. Einstein at the blackboard of the Mount Wilson Observatory Library, January or early February 1931. In light of one of the themes of this paper, we must point out that our Fig. 1 is cut horizontally below Einstein's right arm. Compare with Fig. 5.

Reproduced with permission of FPG International.

How did Einstein do it ?

What was his guiding principle ?

Principle of Equivalence (1907)

Recall Covariance in earlier SR lectures.

Conviction that the laws of nature (physics) should be expressed in the same form in every frame of reference, both non-accelerated (SR) or accelerated (GR) was Einstein's primary motivation that led him to the general theory of relativity …

sometimes called General Covariance

Special Relativity Reminders : 2 axioms !

1) The laws of physics are the same.

2) The velocity of light in vacuo is the same.

Sander Bais

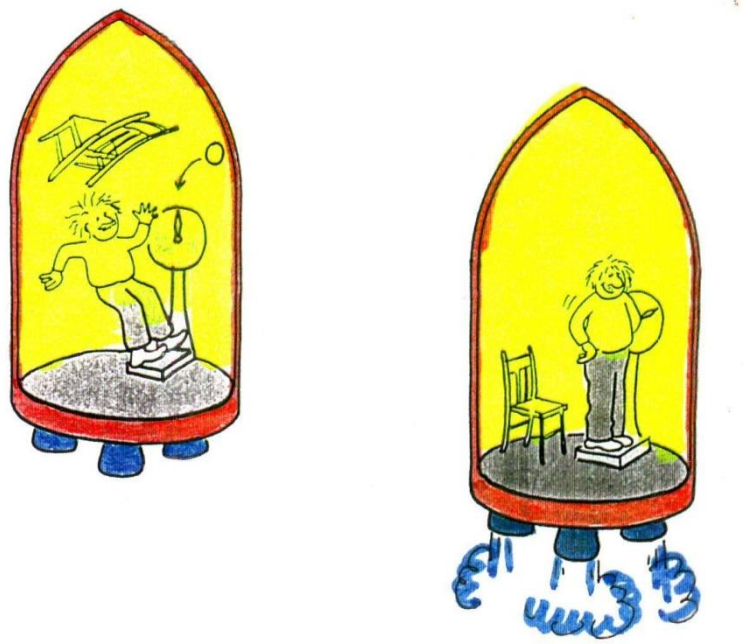
Some books :

1) Principle of Relativity (Newton's 1st Law)

2) Principle of the constancy of the speed of light

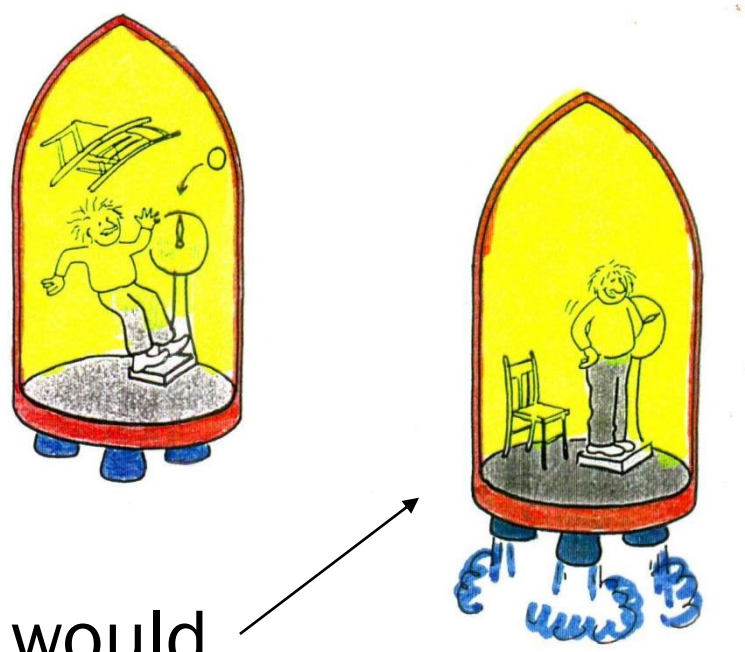
Principle of Equivalence

Consider a spaceship far away from gravitational influence. This spacecraft can be at rest or in uniform motion with respect to distance stars.



Principle of Equivalence

Consider a spaceship far away from gravitational influence. This spacecraft can be at rest or in uniform motion with respect to distance stars.

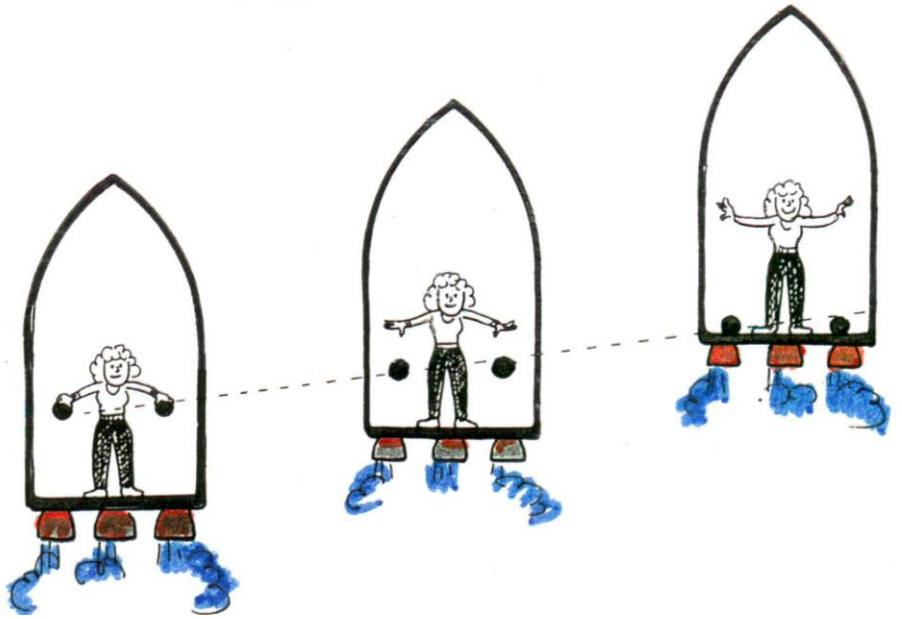


Spaceship moving at g m/s^2, the man would be convinced that the spaceship is at rest on the surface of the earth.

Principle of Equivalence

Drop 2 objects.

To the observer inside the accelerating spaceship, the golden ball and paper ball will fall at the same rate (together).



Impossible to distinguish between gravitation and acceleration.

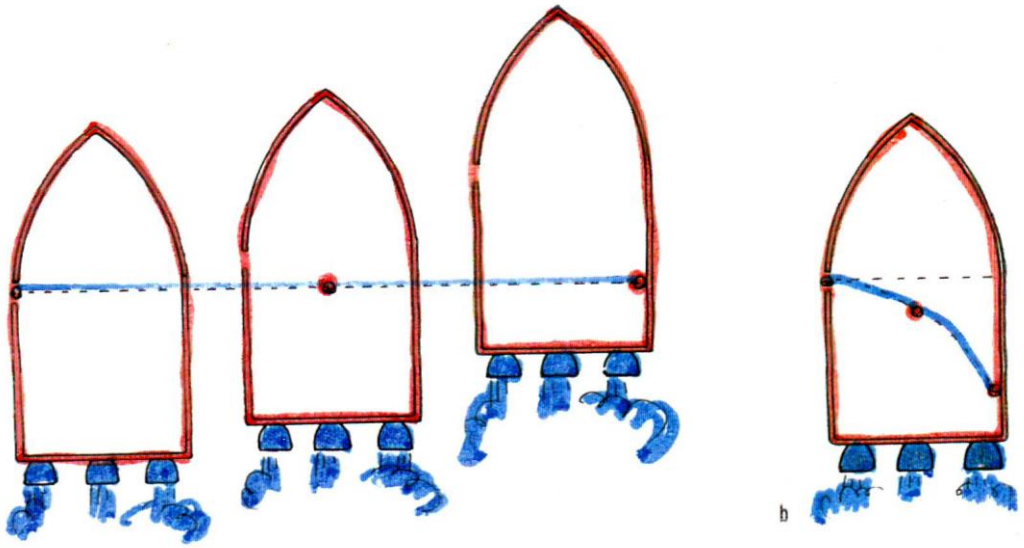
What happens to the balls, if the spaceship is moving at constant velocity?

https://www.youtube.com/watch?v=E43-CfukEgs

Principle of Equivalence (balls)

Throw a ball horizontally.

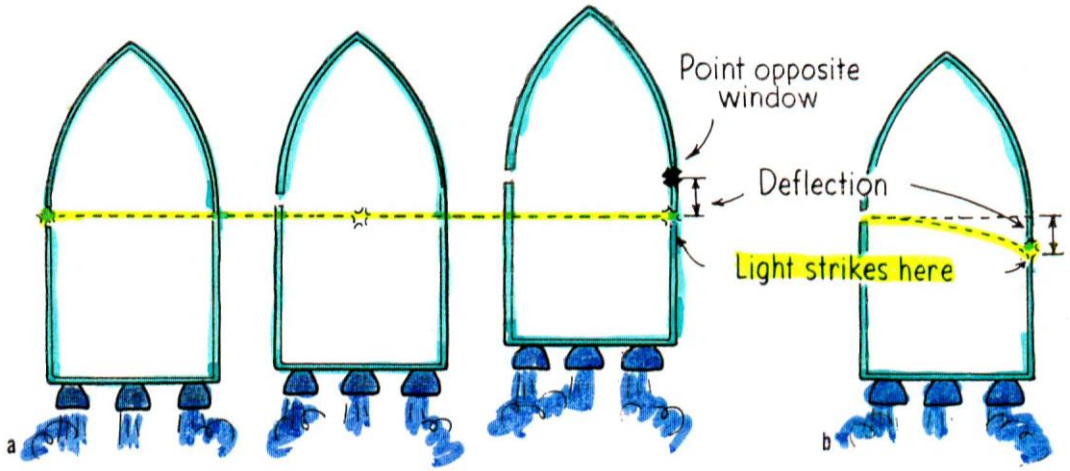
An observer outside the spaceship still sees a straight line path of the ball, but to an observer in the accelerating spaceship, the path is curved: parabola.



Bending of ball's path by "gravity" VS Newton's gravitation attraction.

Principle of Equivalence (light)

Throw a light horizontally.



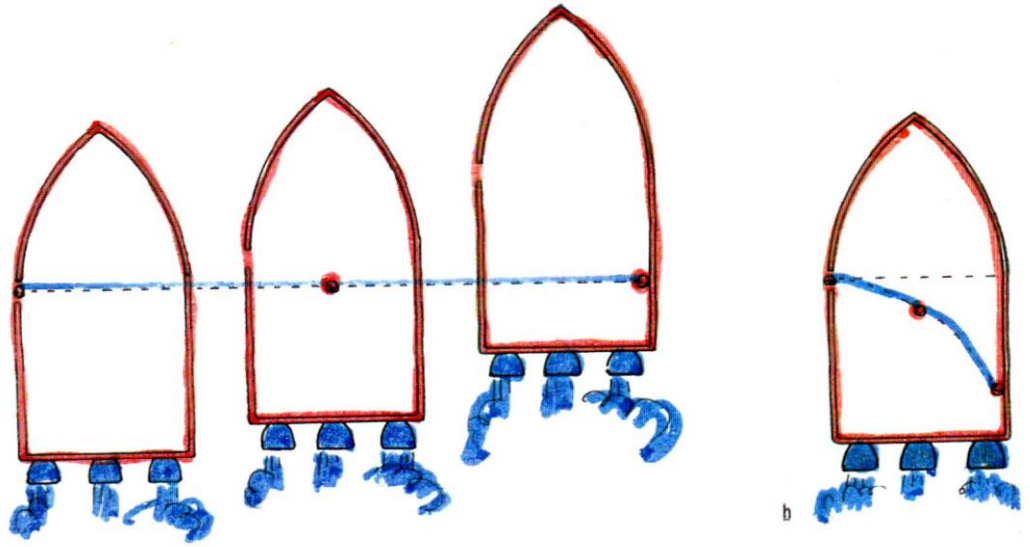
Einstein argues that, the same holds true for a beam of light.

In the accelerating frame of reference, the light ray is deflected downward to the floor just as the thrown ball.

To the inside observer, the light bends as if responding to a gravitational field.

Principle of Equivalence (balls/light)

An observer outside the spaceship still sees a straight line path of the ball, but to an observer in the accelerating spaceship, the path is curved: parabola.



Bending of balls/light by gravity VS Newton's gravitation attraction.

Why call Principle ?

Rather grand word !

Principles (Scientific) are introduced in order to allow some progress to be made when one has no experimental data to go by.

Peter Coles
Cosmologist

How is EP related to Relativity ?

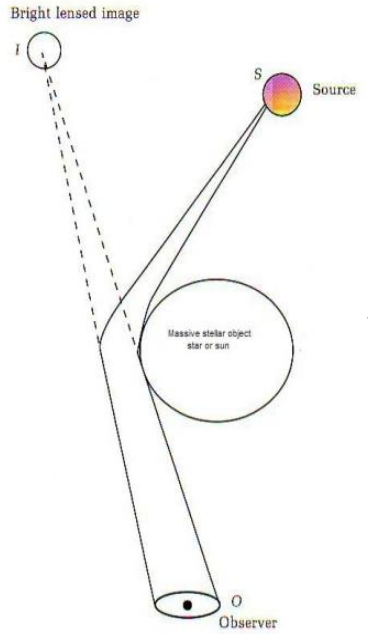
Equivalence Principle applies to all physics.

Einstein now has a basis for saying acceleration … like uniform motion as you know is relative.

Because the distinction between gravity and acceleration dependence on the frame of reference chosen. What looks like gravity from one point of view looks like acceleration from another.

I. M Egdall

Eddington (1919 Solar Eclipse)



Deflection of 1.75 sec of arc

Newton's Theory : gravitation is an interaction between masses.
i. e. a moving ball curves because of the interaction between its mass & the mass of the earth.

Einstein's Theory : It is the same for light. Light is pure energy and massless. It may be mass-less but not energy-less.
Gravity "*pulls*" on the energy of light because energy is equivalent to mass.

Paul Hewitt

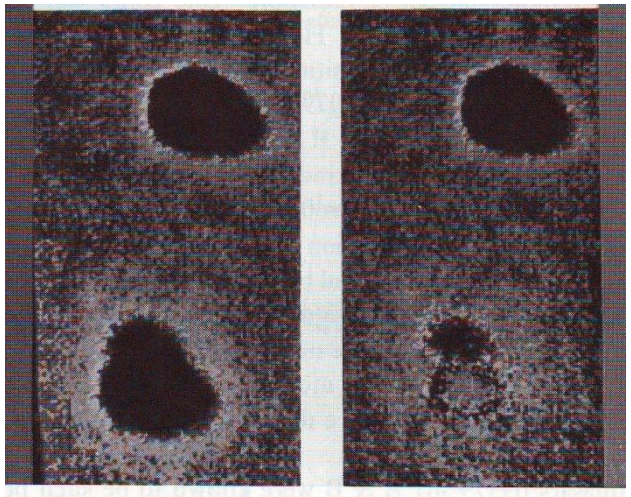
Nowadays every Tom, Dick and Harry thinks he knows what a photon is, but he is mistaken".

A. Einstein (shortly before he died)

More Evidences !

Gravitational Lensing

Cosmic illusions !

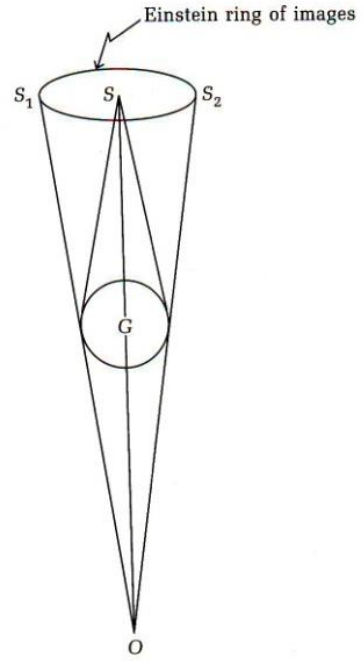


2 Raw images

(from the same or 2 different Quasar sources)

Multiple Raw images from the same MACHO source

Einstein's Ring



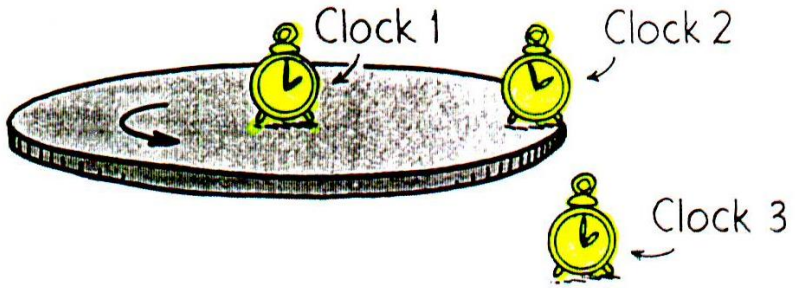
Some consequences

and results of General Relativity !

Gravity and Time

General Relativity tells us that gravitation causes time to slow down.

Consider: Clock 1 = Clock 3, why?



To clock 3, the slower clock 2 on the rim is due to its motion.

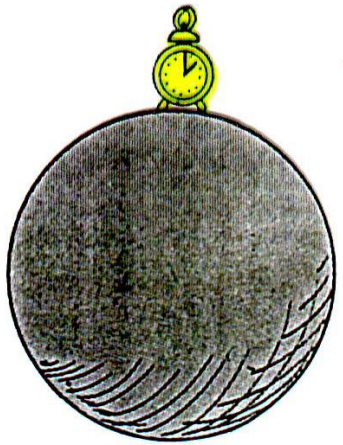
To clock 1, the slower clock 2 on the rim is due to the centrifugal / centripetal force ("accelerating" force) acting on the clock at the rim.

Gravity and Time

General Relativity tells us that gravitation causes time to slow down.

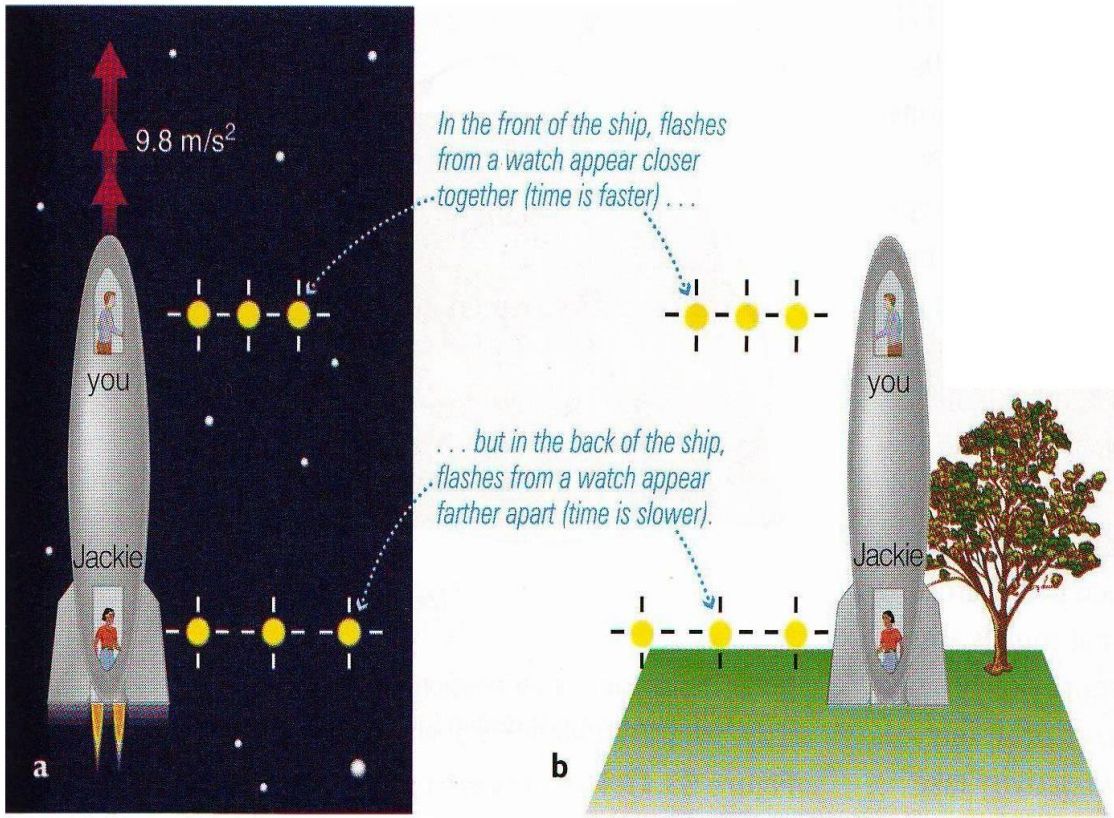
A CEO working on the ground floor of a tall city skyscraper will age more slowly than his workers working on the top floor.

Not sure why condominiums are so expensive on higher floors … pent-house ?



Note: The slowing down of clocks will apply to all clocks whether physical, chemical or biological.

How time slows down in an accelerated frame ?



Reading Assignment

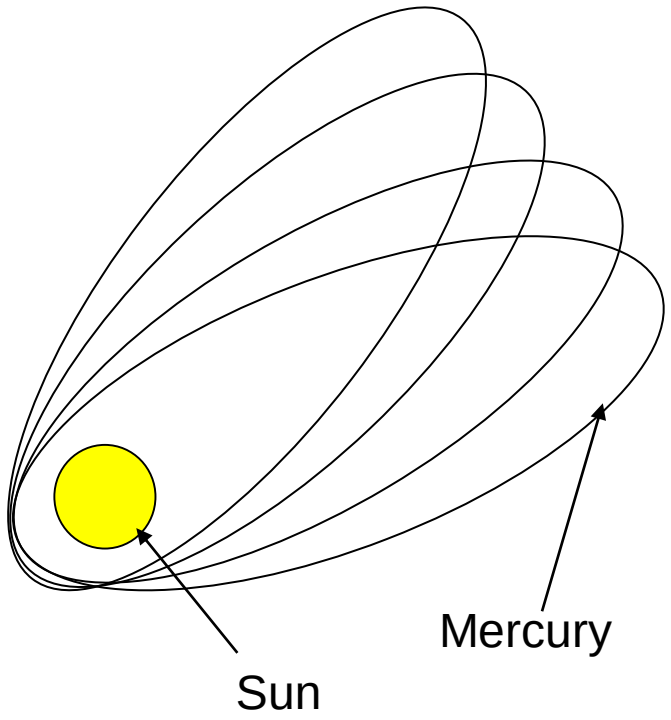
a In an *accelerating* spaceship (but *not* in one at constant velocity), time must run faster at the front end and more slowly at the back end. The yellow dots represent the flashes from the watches, and the spacing between the dots represents the time between the flashes.

b By the equivalence principle, time must also run more slowly at lower altitudes in a gravitational field.

Gravity causes time to run more slowly at lower altitudes than at higher altitudes, an effect called *gravitational time dilation.* (Note that the effect occurs even in a uniform gravitational field; that is, it does not depend on the additional fact that gravity tends to weaken at higher altitudes.)

Some Evidences !

Gravity and Space (Perihelion of Mercury)



Einstein's Field Equation applied to Mercury's orbit predicted an extra 43 seconds of arc per century.

(575 – 532 = 43).

Leverrier proposed Vulcan ! 1860

Gravity and Time

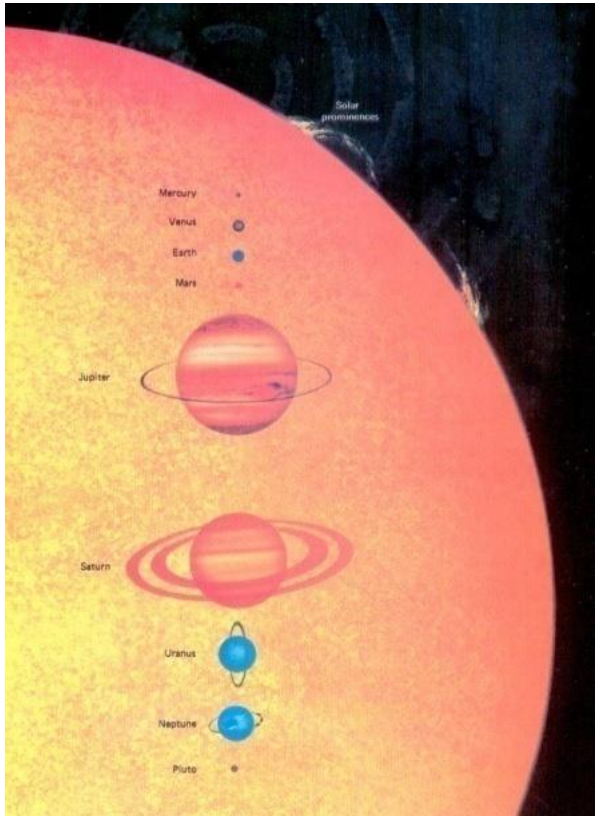
General Relativity tells us that gravitation causes time to slow down.

An atom (a kind of “clock”) in the sun should emit light of a lower frequency than light emitted by the same kind of atom on the earth.

If a star were to shrink, its surface moves inward to ever stronger gravity which in turn causes time on its surface to slow down progressively.

The observer outside the star perceives time stops (frozen in time) eventually for a man approaching a massive star.

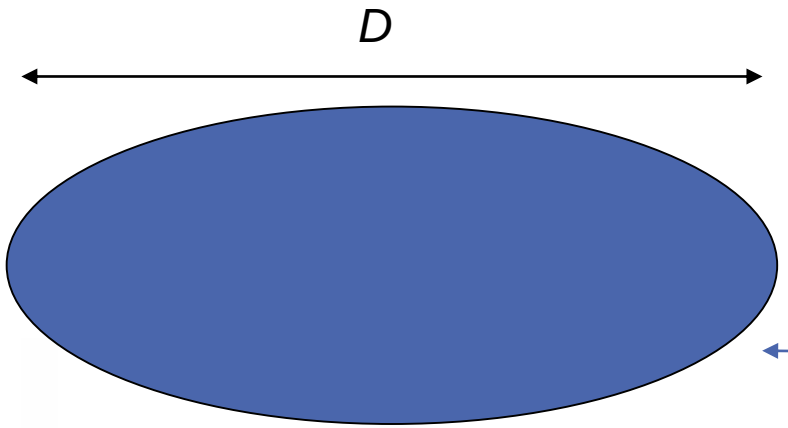
Gravitational Red Shift



Why are we so interested in studying Geometry ?

or Topology ?

Gravity and Space (New Geometry)



Rotating Disc

Non - Rotating $\frac{C}{D} = \pi$

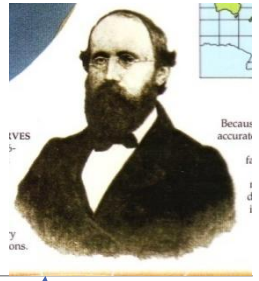
Rotating $\frac{C}{D} \neq \pi$

Gravity is a manifestation of Spacetime Geometry

Since distance measurements // to and around the circumference are affected hence …

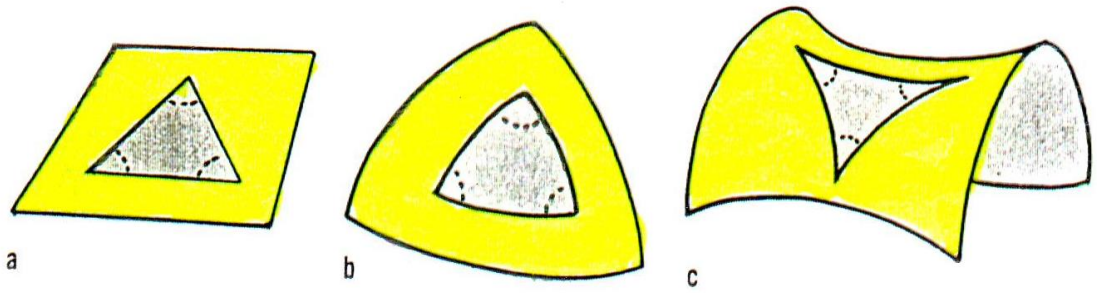
The ruler will appear contracted to any observer not moving along with the stick.

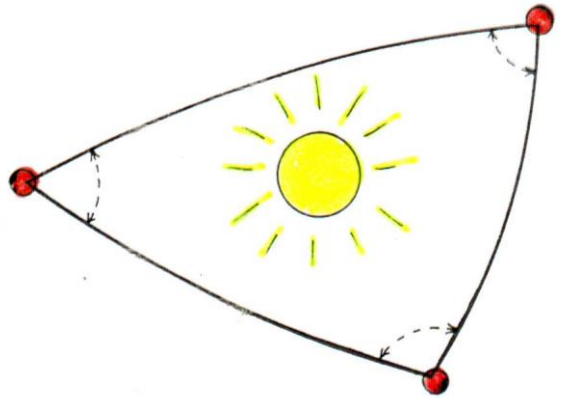
Gravity and Space (New Geometry)



What are Geodesics ? … ie. shortest path

Gravity causes Space to be Non - Euclidean …. Riemannian





The light rays joining the 3 celestial bodies form a triangle. Since light passing near the sun bends, the sum of the angles of triangle is greater than 180 degrees or less than 180^0.

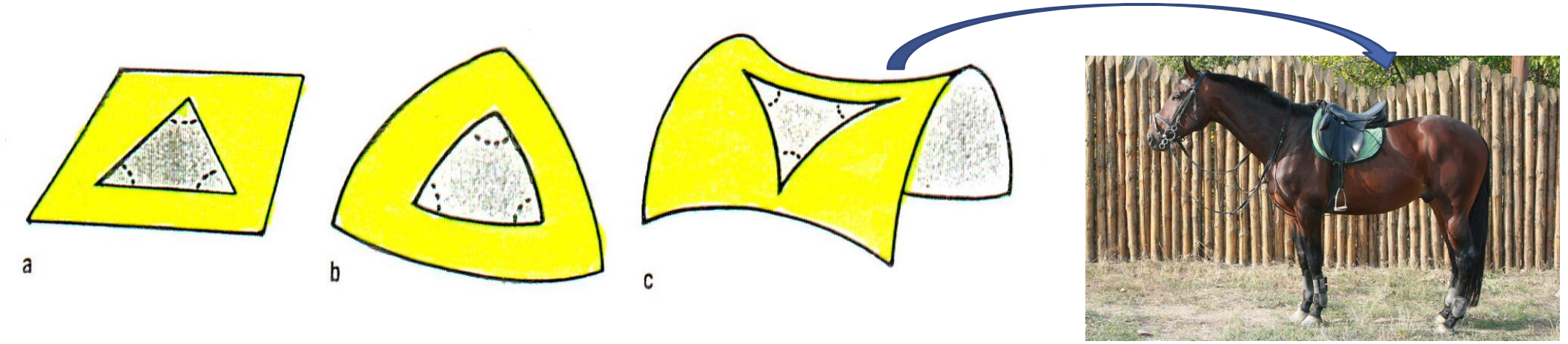
Gravity and Space (New Geometry)

The whole Universe may have an overall curvature.

If it is negatively curved, it is open ended and extends without limit. e.g. saddle point/curve.

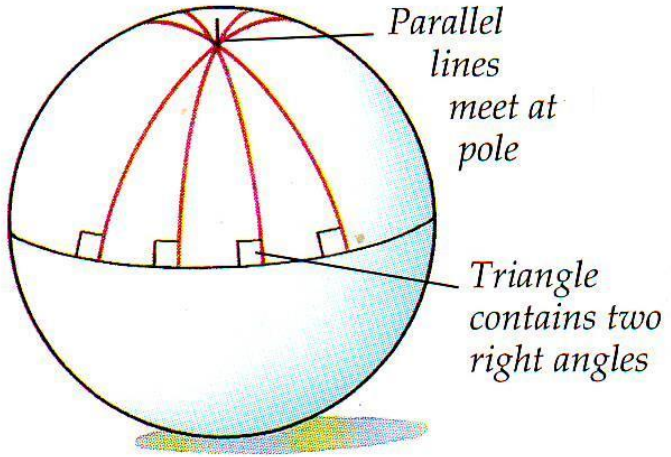
If it is positively curved, it closes in on itself. e.g. earth. If one were to look infinitely into space through an ideal telescope, you would see the back of your own head. Ha !

If the curvature is zero; the dimensional space on a flat piece of paper is flat.

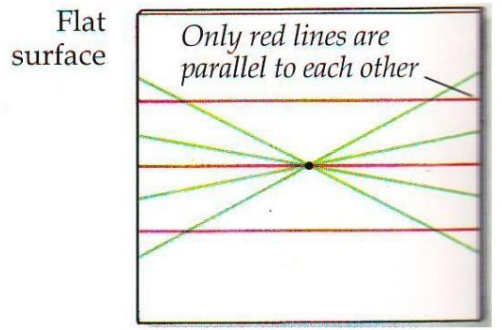


Reading Assignment !

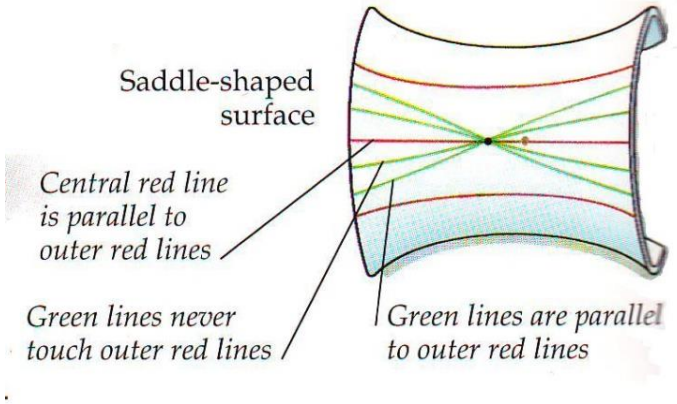
Gravity and Space (New Geometry)



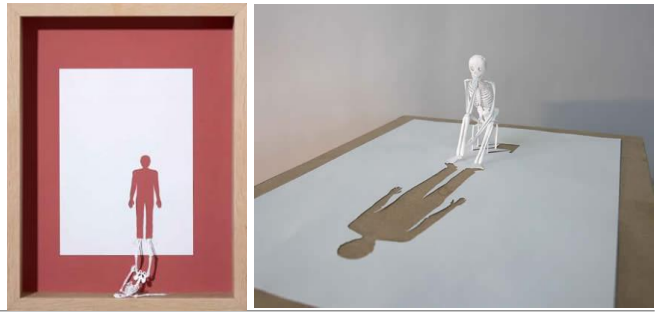
SURPRISING TRIANGLES
The angles of a triangle on a spherical surface add up to more than 180°. Lines of longitude cross the equator at right angles (90°) and are all parallel to one another, but meet each other at the poles, making triangles.



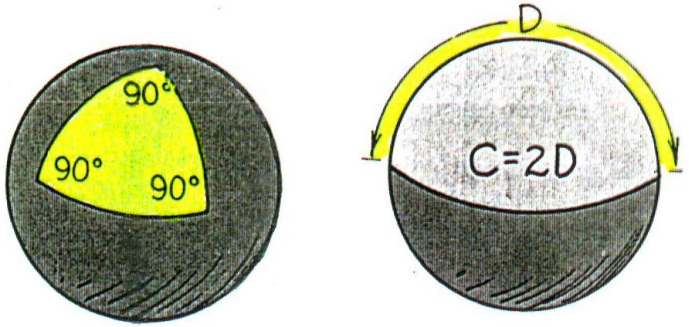
FLAT VERSUS CURVED
On a flat surface the angles of a triangle add up to 180° and parallel lines always stay the same distance apart. Gauss discovered that different rules apply on an "open" surface, curved like a saddle. Lines can be drawn which are each parallel to a third line because they never cross it, but which cross each other

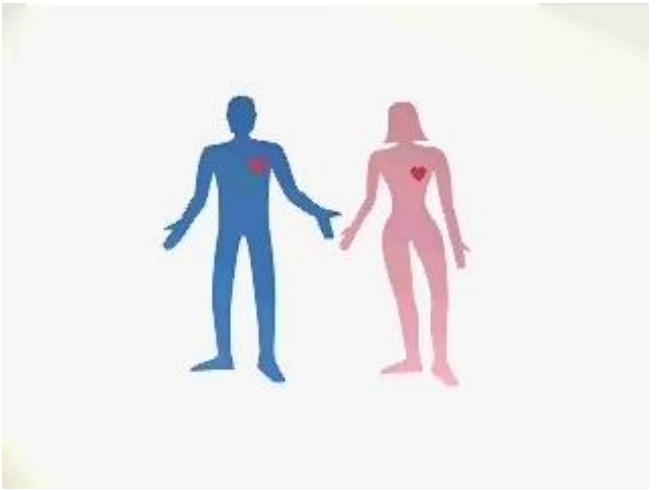


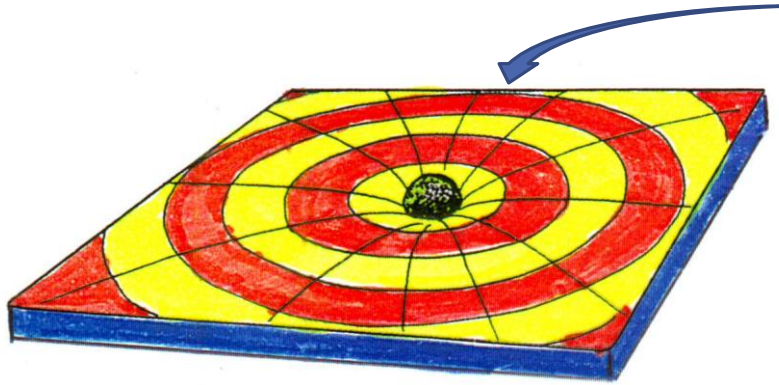
Gravity and Space (New Geometry)



Reminder





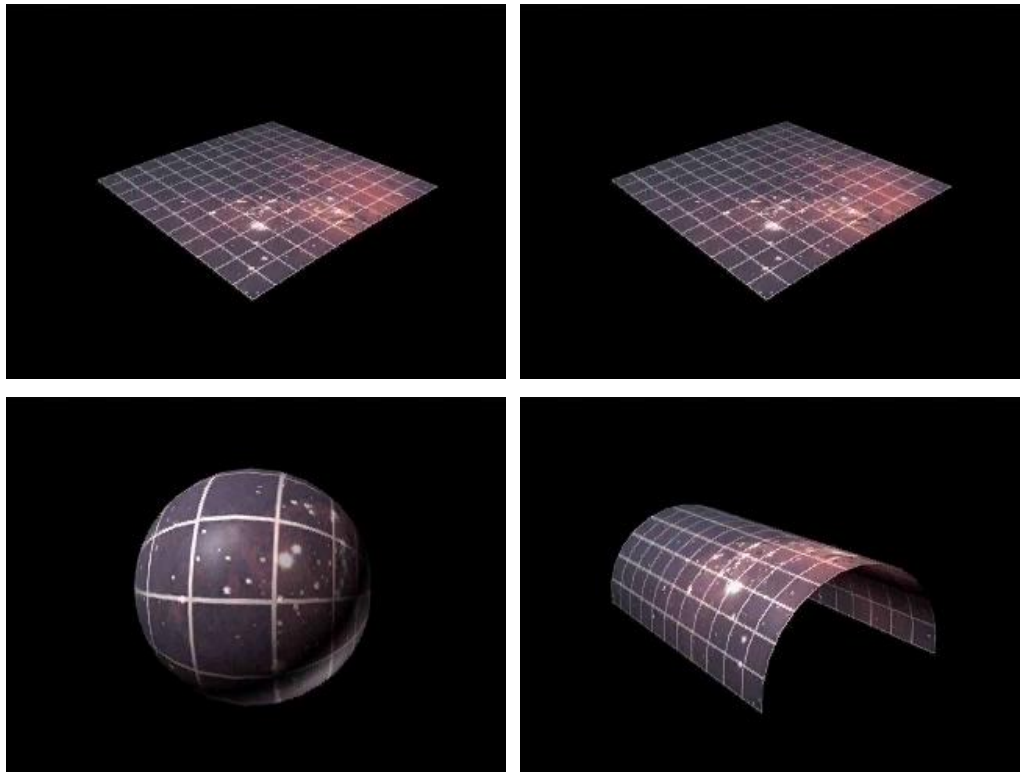


A 2 dim analogy of a 4 dim warped space-time. Space time near a star is curved in a way similar to the surface of water bed when a heavy ball rests on it.

Gravity and Space (New Geometry)

The presence of matter results in the curvature of space.

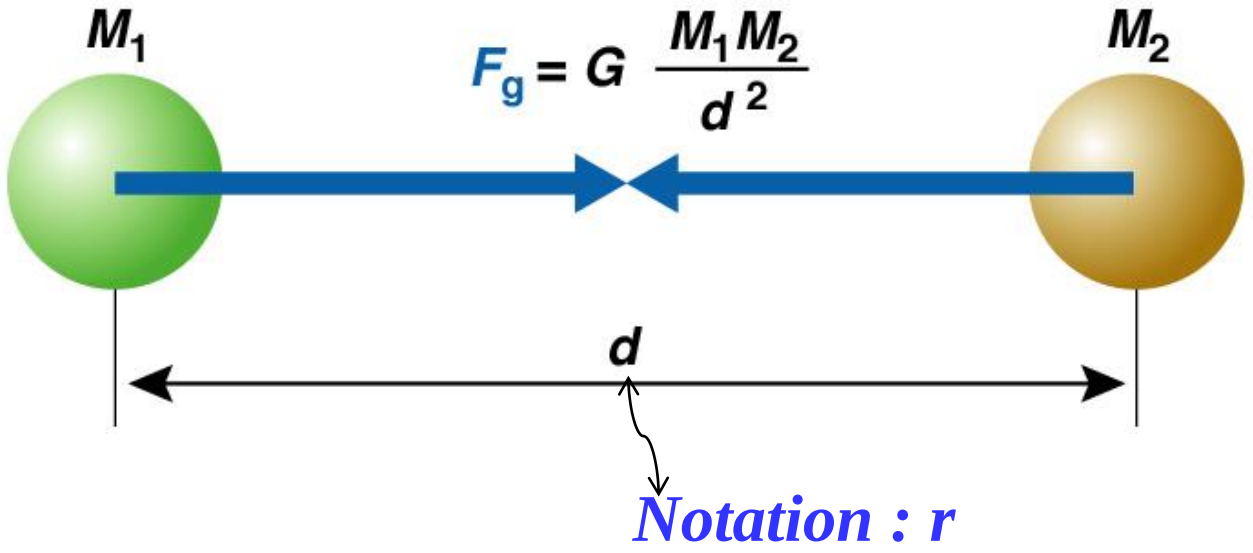
We abandon the notion of "FORCE"; we may visualise masses responding in their motion to the warping of Space-time they inhabit.

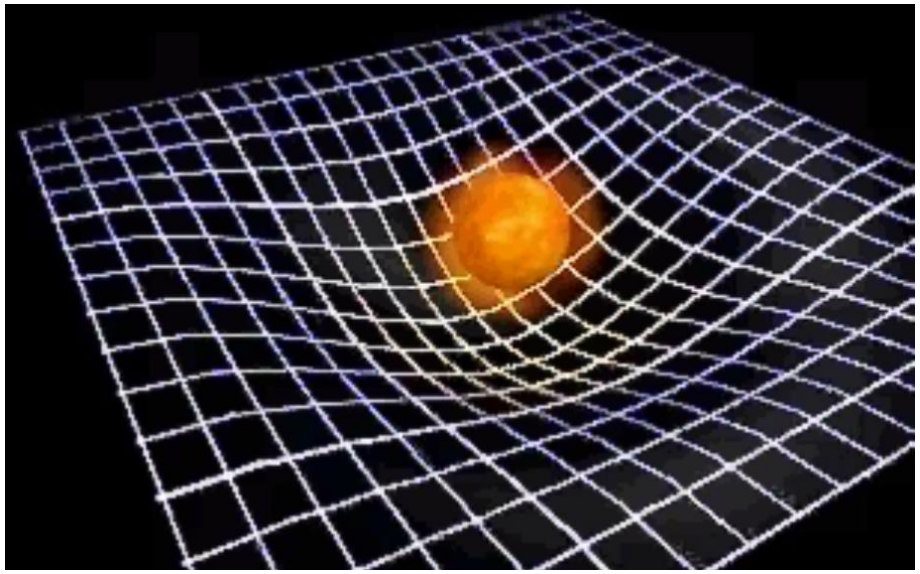


What determines the strength of gravity?

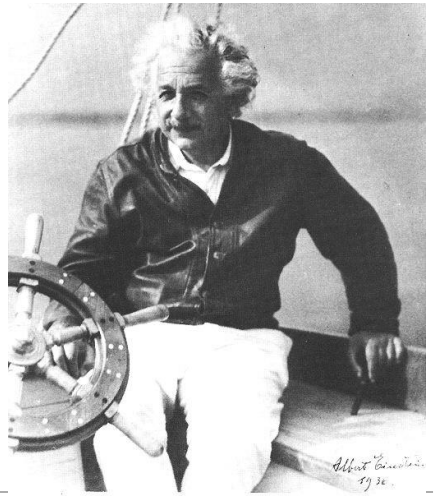
The **Universal Law of Gravitation** (“***action at a distance***”) **:**

1. Every mass attracts every other mass.
2. Attraction is *directly* proportional to the product of their masses.
3. Attraction is *inversely* proportional to the *square* of the distance between their centers.

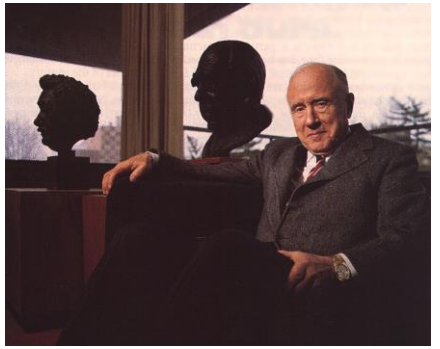




Space determines how Mass should move.
Mass determines how Space should curve.

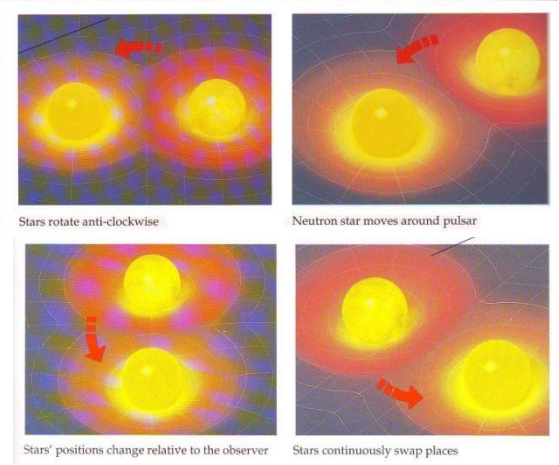


John. A. Wheeler



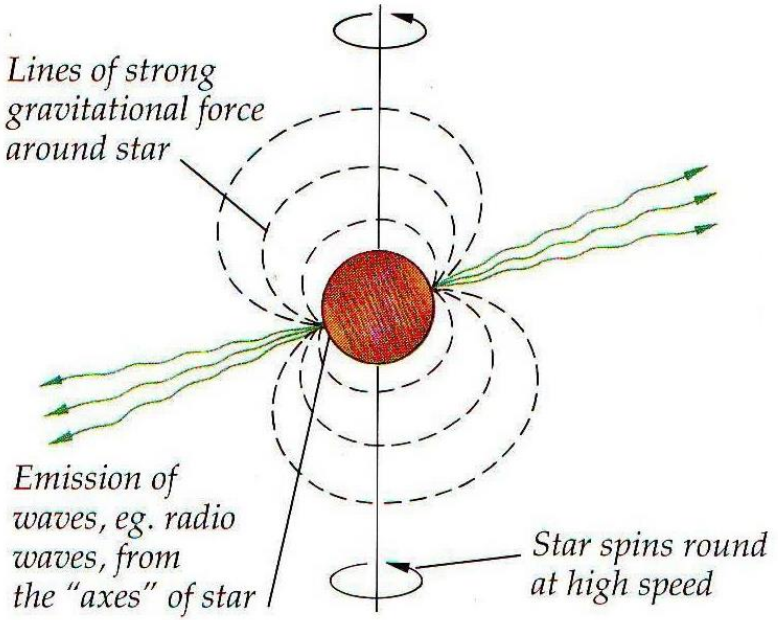
Other Evidences !

Gravitational Waves (PSR 1913+16)




SEARCH & DISCOVERY

HULSE AND TAYLOR WIN NOBEL PRIZE FOR DISCOVERING BINARY PULSAR



WHAT IS A PULSAR?

The most dense concentrations of matter are neutron stars. A neutron star is little bigger than a mountain, but contains as much mass as the Sun. The star has the density of an atomic nucleus (p. 58). Some neutron stars have strong magnetic fields, and beam out radio waves like a lighthouse. They are called pulsars. Changes in the pulsar spin show up as changes in the lighthouse effect.

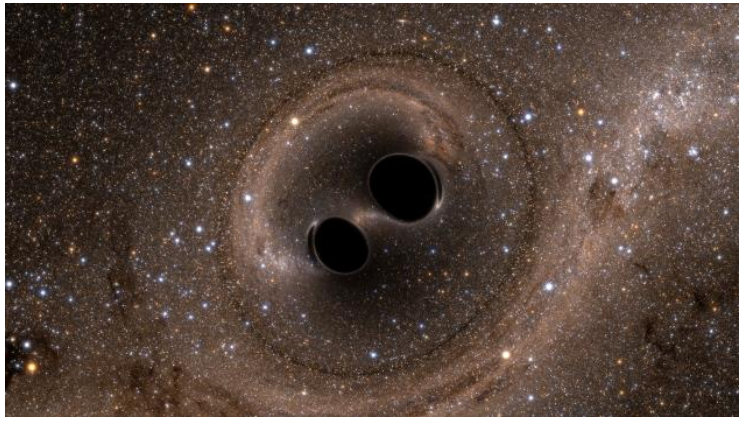
Hulse and Taylor (Binary Pulsar, 1978) shared a Nobel Prize in 1993. This pulsar emit pulses with a period of 0.059 029 995 270 9 seconds. This work underscores the importance of detecting gravitational (very weak) radiation directly.

Gravitational Waves

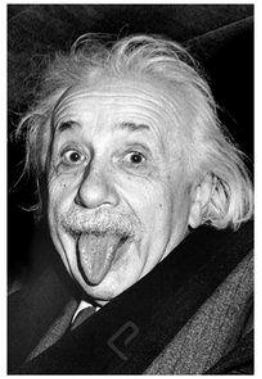
When an object moves, the surrounding warp of space and time moves to readjust to a new position. This readjustments produce ripples in the overall geometry of spacetime.

This ripples travel outward from the gravitational sources at the speed of light and are called gravitational waves.

Gravitational wave detection wins physics Nobel



A computer simulation of two black holes colliding, which generates gravitational waves.



Rainer Weiss (left), Barry Barish (centre), and Kip Thorne (right), who led work to detect gravitational waves. Nobel Prize 2017

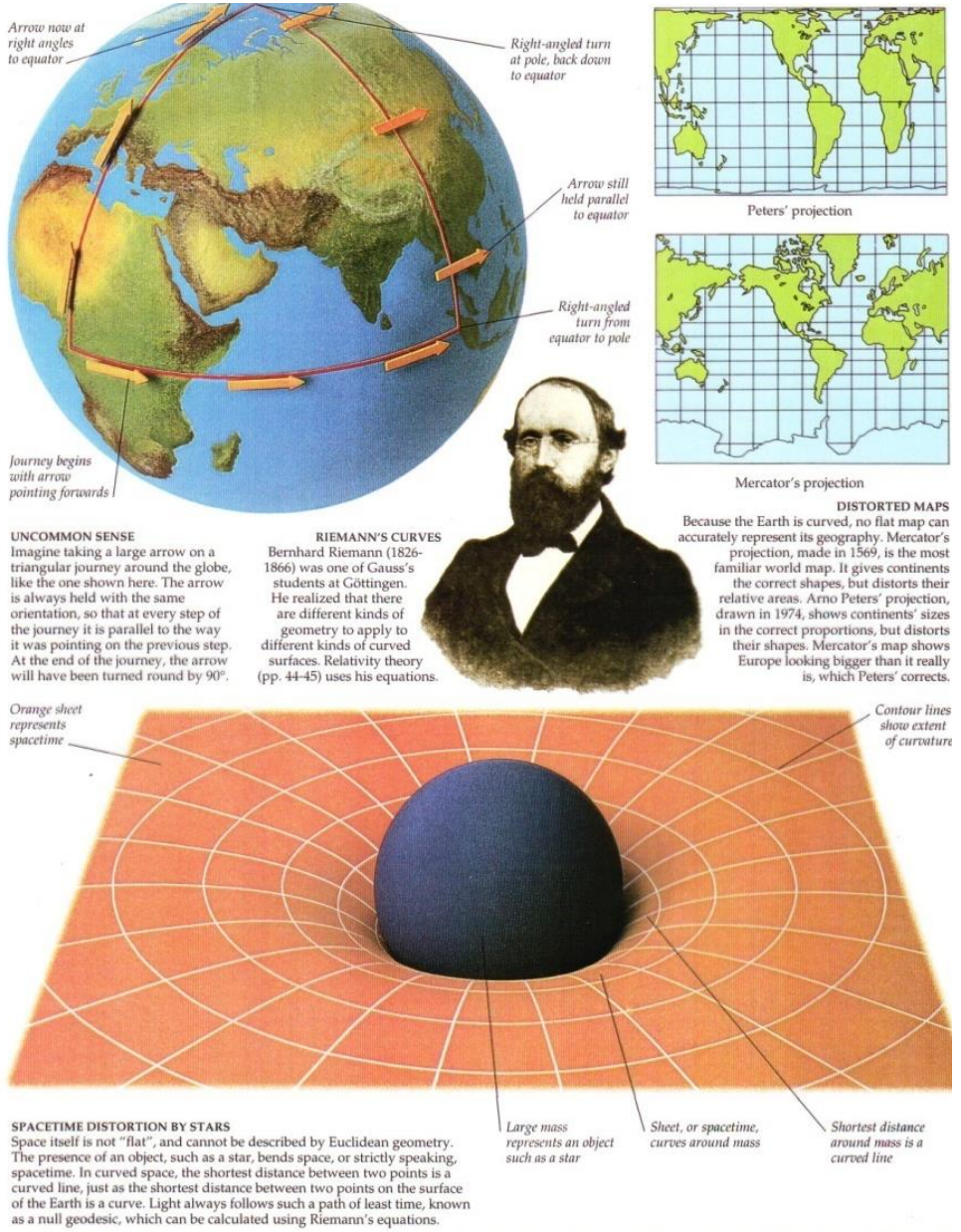
Gravitywaves.MOV

Gravitational Waves

Gravitational Waves

Shake your hands back and forth, you would have produced a gravitational wave. It is not very strong but it should exists … at least in theory as in Electromagnetic waves.

Generate Gravit**ons** !



Newtonian & Einsteinian Gravitation Theory

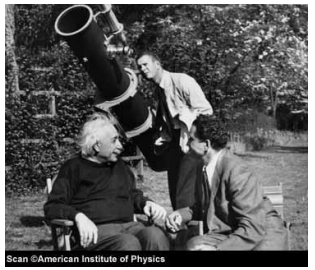
Newtonian physics is a special case of the broader theory of relativity. Also Einstein's field equations must reduce to the Newtonian equation for gravity in the weak field limit.

Newtonian law of gravitation is still an accurate description for most of the interactions between bodies in the solar system and deep skies.

So one can calculate the orbits of comets and asteriods even predict the existence of undiscovered planets.

But in regions of intense gravitational field, Newtonian description of gravity is not adequate.

Conceptual Physics of the Universe



Seen from today's understanding of the Universe, we find our importance lies in being very much a part of nature, not apart from it. We are the part of nature that is becoming more and more conscious of itself.

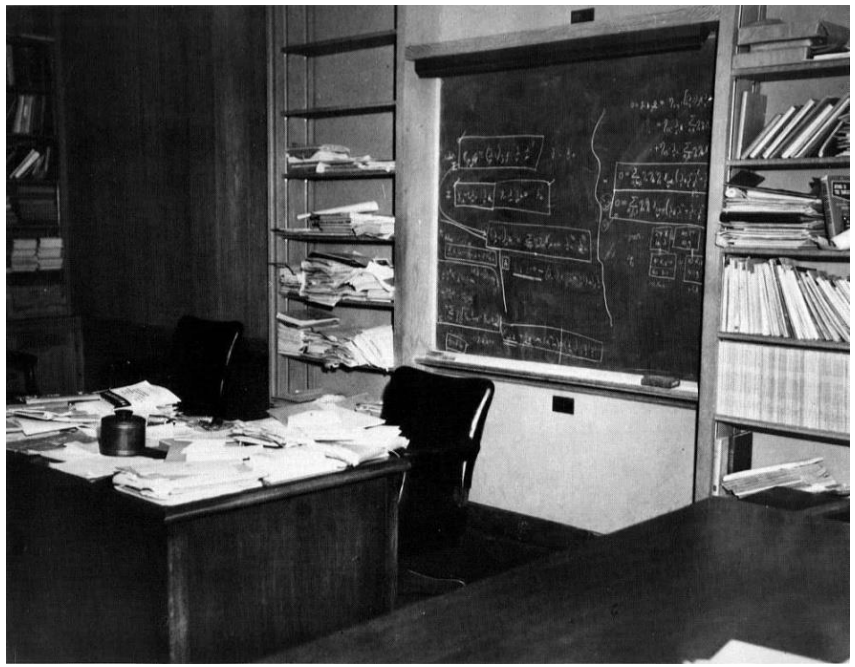
In going on with these experiments, how many pretty systems do we build, which we soon find ourselves obliged to destroy ?

Benjamin Franklin

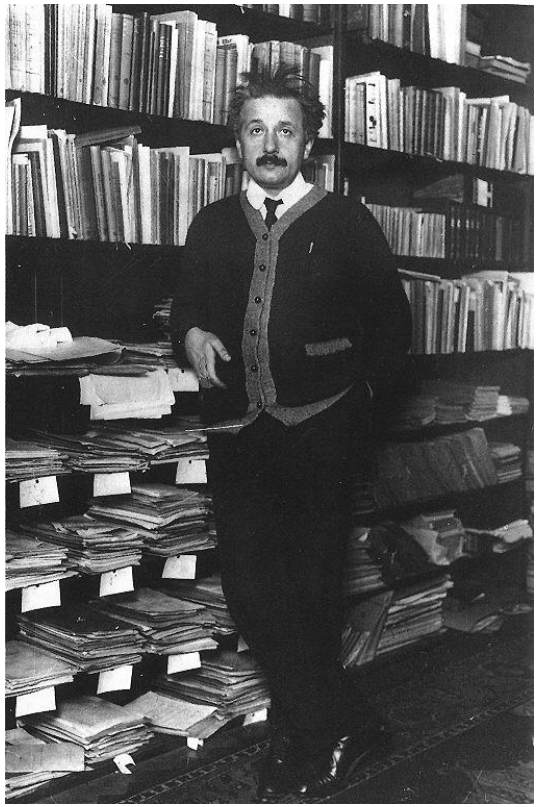
An important message of Science, however, is that not knowing is okay. … it's essential to doubt those who claim to be privy to all the answers – those who claim attainment of absolute certainty. The tragic part of our past is replete with the power these people wielded. The bright part of our future will be devoid of their influence … Acknowledging and accepting your limitations is the beginning of wisdom.

Paul Hewitt

Einstein's : Success = X + Y + Z



Einstein's last office Princeton 1955



http://www.youtube.com/watch?v=xaKJL7ZKPrY

The difficulty !

The difficulty lies, not in the new ideas, but in escaping from the old ones, which ramify, for those brought up as most of us have been, into every corner of our minds.

J.M. Keynes

(1883-1946)