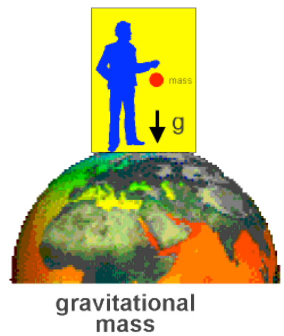
How do I tell there's gravity?

Anything I stop holding up accelerates downward at 9.8 m/s² (regardless of its mass)



How do I tell there's gravity?

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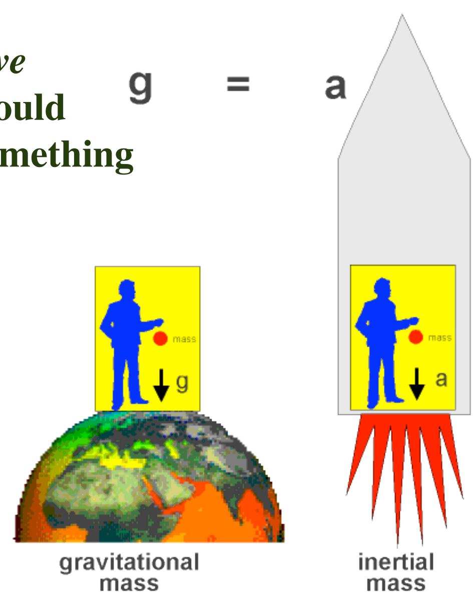
But: since all we can observe is *relative* position and *relative* velocity, what would I see if everything else sat still, but something accelerated *me* upward at 9.8 m/s² ?

Exactly the same thing!



The equivalence principle

Since there is no *observable* difference between the presence of an external gravitational force and the simple fact of looking at things from an accelerated reference frame, there is no *physical* difference.

What looks like gravity to one observer looks like acceleration to another.

(As in SR, two different descriptions of the same reality – the laws should not care whose perspective we use. But in SR we learned how to talk from the perspective of different "inertial frames"; now we need to discuss a more general kind of reference frame.)

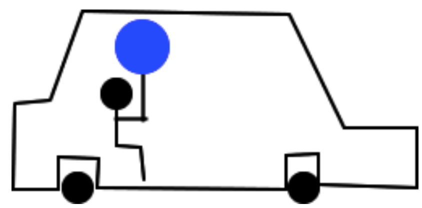
(In a freely-falling frame, you think there's no gravity at all)

Thought experiment

You are in a car, holding a floating balloon by the string.

The car suddenly brakes.

Which way does the balloon go, relative to the car?

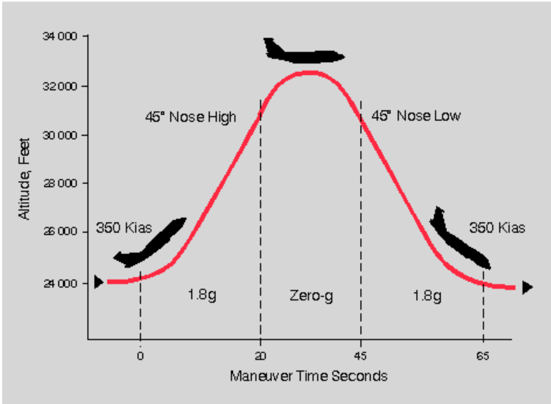


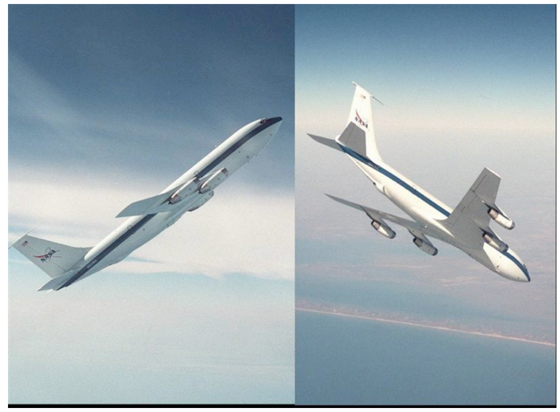
NOTE: if you haven't had the occasion to, ride the elevators in the tower section of the physics building, and check out the "gravimeters"

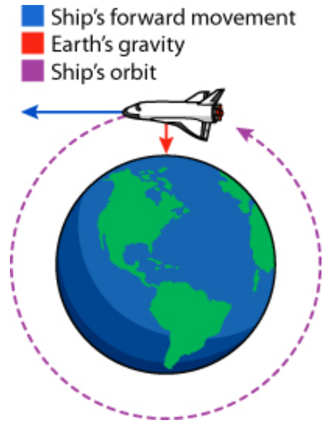
Inertial frames

So: the "inertial frames" we imagined in special relativity are actually *freely falling* frames -- the world as viewed by a skydiver or an astronaut. From their point of view, objects really do keep moving at constant velocity.
From *our* point of view standing on the Earth (not an inertial frame), objects don't keep moving at constant velocity, but accelerate downwards.

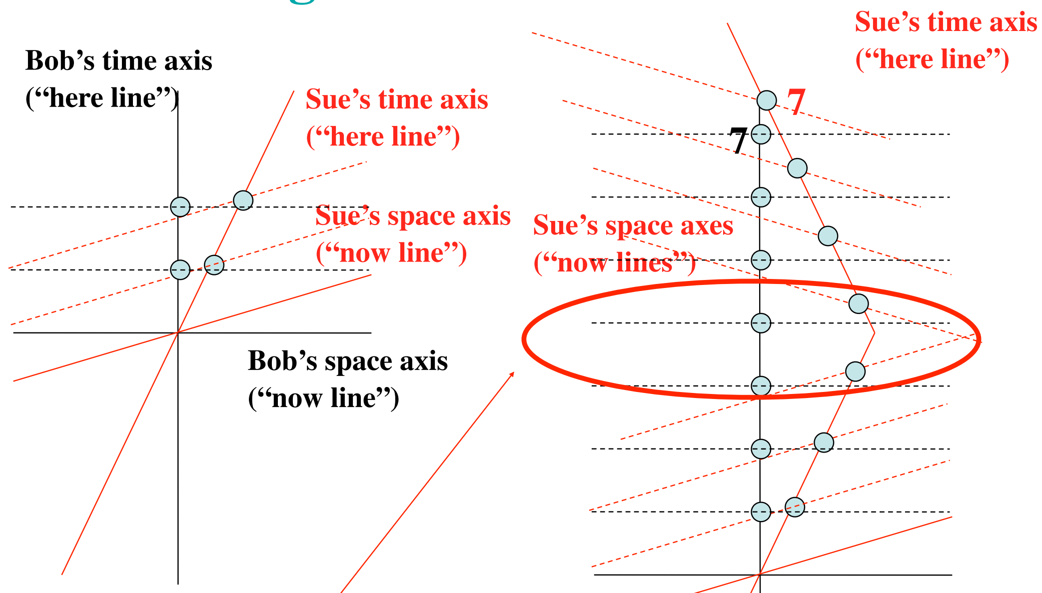
The space shuttles fly a few hundred km above the surface of the Earth.
QUESTION: how big is the force of gravity there?





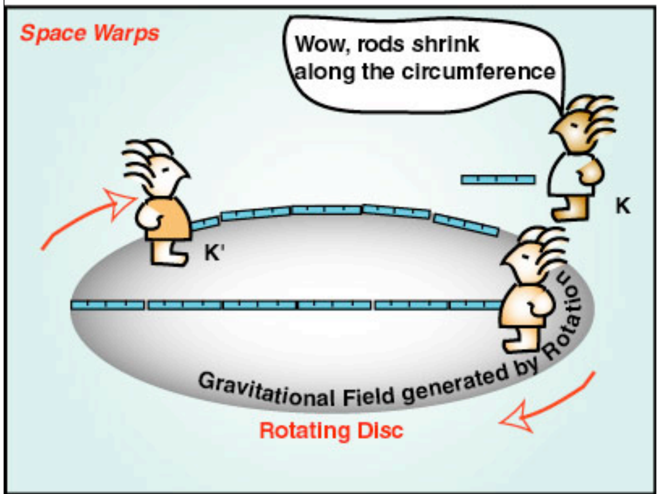


Remember: acceleration already gave us a headache



Somehow, when Sue started accelerating,
time went haywire.
From her perspective, there's now gravity...

Acceleration modifies geometry



If I run around the circle (accelerating centripetally to do so), then rulers along the direction I run shorten, so the circumference I measure gets longer.
But rulers perpendicular to my motion are unchanged, so the radius seems the same.

So is the circumference π times the diameter, or not?

Einstein: in an *accelerated* frame, the formula for distance gets modified.

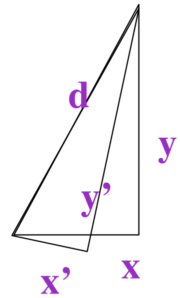
General relativity:

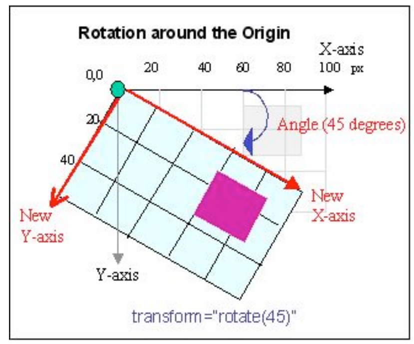
Instead of just writing x and t from the point of view of any *non-accelerating* observer, can we find a way to rewrite them no matter *what* the observer is doing? (Include acceleration.)

Then if we learn how to describe acceleration as some property of spacetime, we will have learned how to describe gravity as some property of spacetime as well.

What do we mean when we say physics is about geometry?

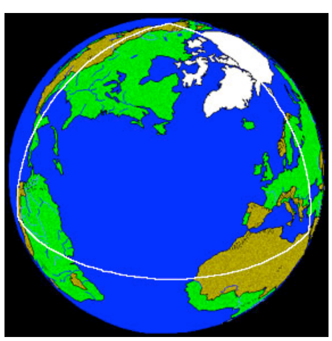
Pythagoras taught us that no matter which (perpendicular) axes you liked to use, you could find the distance from a simple formula. This formula is part of the basis of (Euclidean*) geometry.





*- despite centuries of attempts, no one succeeded in *proving* the final postulate of Euclid's, that parallel lines never meet. Why not?

Geodesics ("parallel" circles)



If you head straight north from Quito and I head straight north from Kampala, we will both meet at the North pole.

Every other axiom of Euclid's still holds true on the surface of the globe. Geometry of curved space.

Pythagoras is wrong: two sides of this right triangle are 10 000 km, but the "hypotenuse" is also 10 000 km (not 14 142 km).

Worse, there isn't one hypotenuse; every angle is a right angle, so they add up to 270^o instead of 180^o.

And the equator is twice the "diameter," not π times...

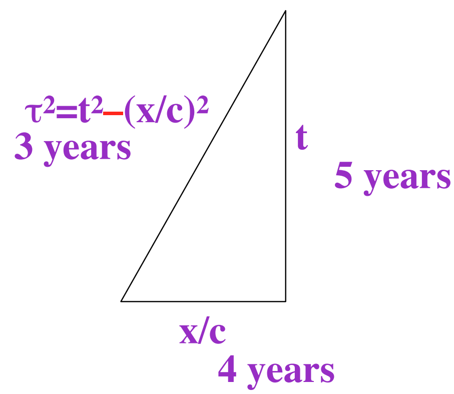
What do we mean when we say physics is about geometry?

If we know what formula tells us how to calculate the distances from our "coordinates" (eg latitude & longitude), we know the geometry.

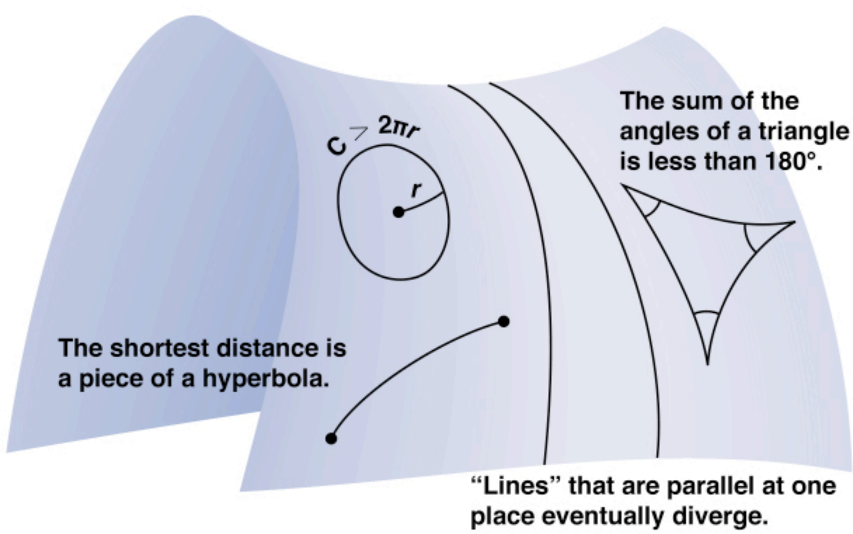
Einstein realized distance *isn't* the same for all observers, but "proper time" (the age of the guy *on the ship*) is; he found the formula is

$$\tau^2 = t^2 - (x/c)^2$$

This fixes the geometry of spacetime.



In an *accelerated* frame, the formula for distance gets modified. *Spacetime is curved.*



Geometry as a law of physics

Euclid: the shortest distance between two points is a straight line.

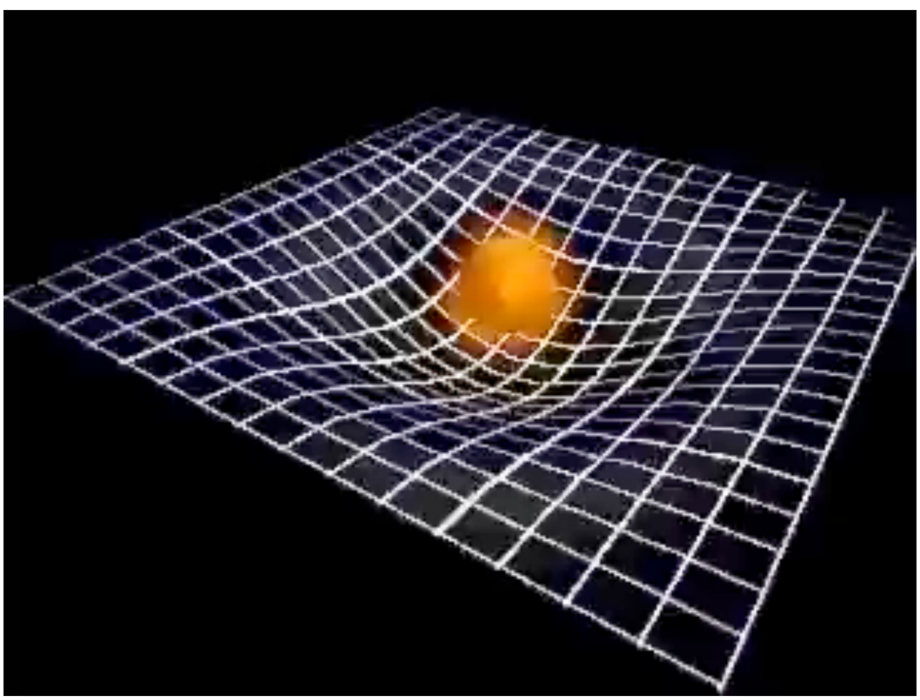
Einstein: the longest *proper time* between two *events* (points in spacetime) is a “geodesic” (the general term for great circles).

In the absence of “real” forces *(because we no longer count gravity!)*, these geodesics are the paths objects follow.

Mass (or energy, which is the same thing) *causes spacetime to curve*; and everything else then moves according to that curvature.

The reason everything accelerates the same way under gravity (meaning that you can’t tell gravity from acceleration) is that we’re all just moving in the same spacetime.

Why does the Earth go around the Sun?



Geometry as a law of physics

If you fell freely with gravity (the floor weren't there to exert some outside force on you, holding you up), then spacetime would look flat.

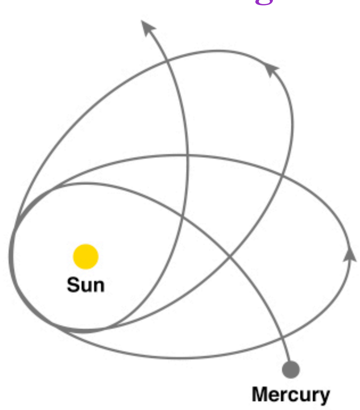
When you accelerate w.r.t this freely-falling frame (as we're all doing now), you have a different *reference frame*.

And in this reference frame, Einstein's "Pythagorean Theorem" is different -- spacetime appears curved.

Objects no longer seem to follow straight paths in spacetime (i.e., move at constant velocities), but to fall towards the Earth, or the Sun -- because they're trying to follow the geodesics of this curved geometry you live in.

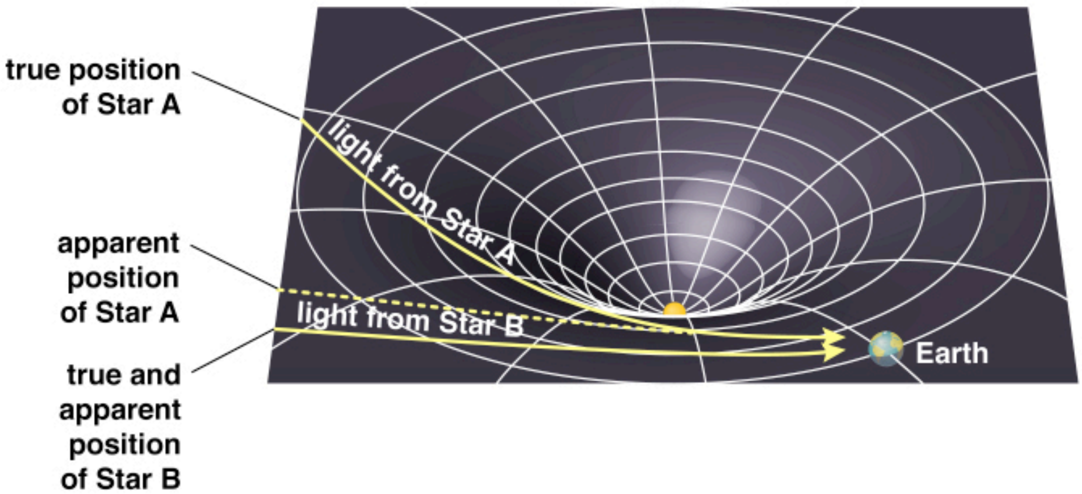
How do we know it's true?

Q: What if experiment doesn't confirm GR?
Einstein: "Then I should feel sorry for the Good Lord. The theory is too beautiful to be wrong."

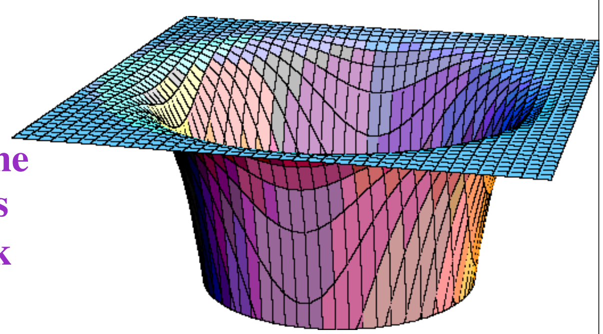


Note: The amount of precession with each orbit is highly exaggerated in this picture.

Eddington's observation



Black holes



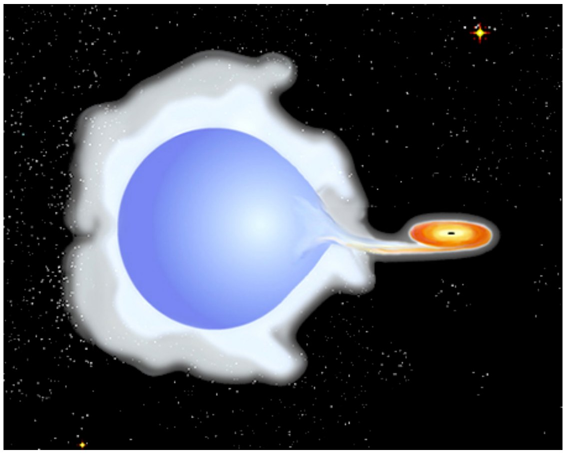
Imagine an object so heavy that even light can never escape.

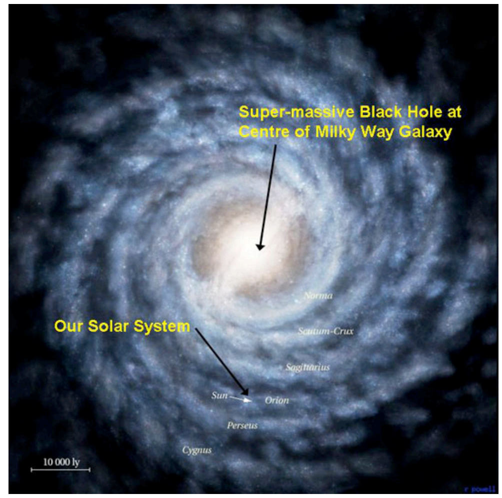
But remember: the "past" is all the places light could have reached us from. Everything inside the black hole is in the future.

An "event horizon" you can't see past. If you could fall in without being ripped apart, you would see the universe *end* behind you...

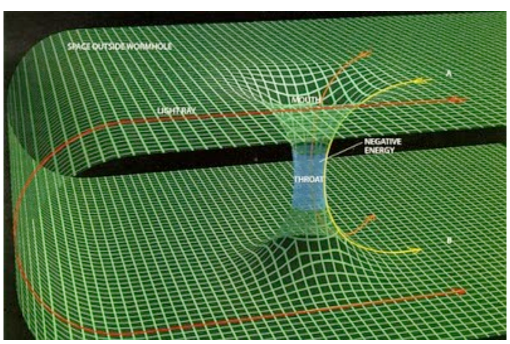
"Black holes have no hair": since nothing ever gets out, you can't tell anything about what the black hole is made of, except how heavy it is (how curved spacetime gets)

How do you “see” a black hole?!



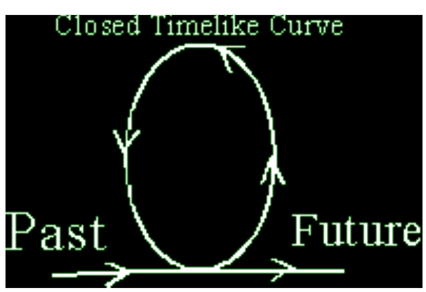


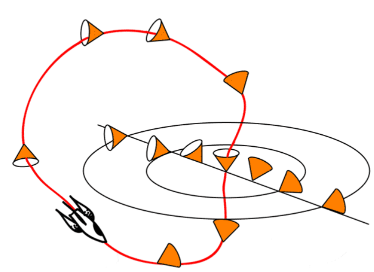
More exotic possibilities



“wormholes”?

“Closed timelike curves”





Gravity Waves

There is *energy* stored in the "stress" of curved spacetime.

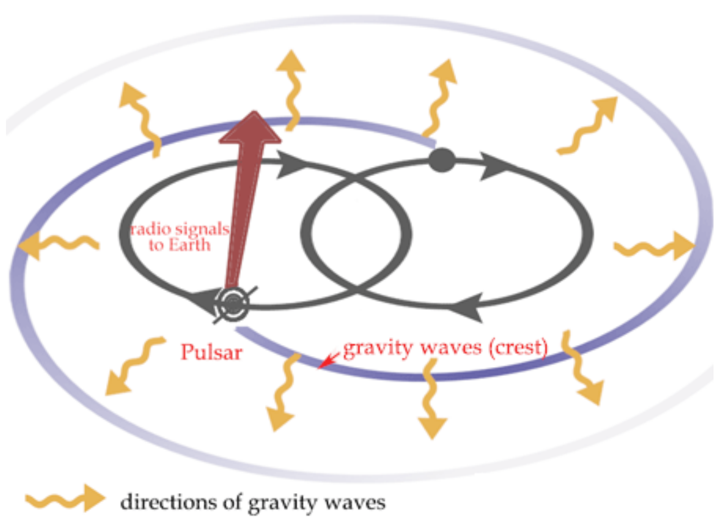
(Remember gravitational potential energy?)

But if an object shakes around on a sheet, won't ripples start propagating in the sheet?

Einstein's equations predict exactly the same thing: *waves of pure gravity*.

Gravity radio???

The binary pulsar system



Hulse & Taylor 1993 Nobel Prize

(none to Eddington... and none to Einstein for GR!)