# Einstein's Theory of Relativity

There are really three theories of relativity:

- Relativity pre-Einstein (Galileo)
- Special Theory of Relativity (1905)
- General Theory of Relativity (1915)

Relativity is concerned with the question: What is the nature of space and time?



#### Absolute space and absolute time:

Suppose that you are on an airplane. At 12:00, you leave your seat to talk to a friend a few rows in front of you. At 12:15, you return to your seat. You might say that: at 12:15, you were at the same point in space where you were at 12:00. However, what would a ground-based person claim?

If the plane were going 600 mi/hr, that person might say: "at 12:15, you were at a point in space 150 miles away from where you were at 12:00."

Who is right? According to Aristotle, space and time are universal and you have moved.

But the Earth is moving around the Sun, and the Sun around the Galaxy and the Galaxy is whizzing through space....

#### Relativity according to Galileo:



"It only ever makes sense to speak of motion relative to something else."

#### Important reflection on Science:

Scientists dream up theories of the world which they test using experiments. Only those things that can be tested by experiment are in the domain of Science...theories are usually flawed, they get improved by the next generation of scientists.

There are <u>NO</u> experiments you can do which will prove that you are in absolute motion on the airplane (providing it is moving at a constant velocity). The best you can do is say "I am at rest relative to the airplane" or "I am moving relative to the ground." It just doesn't make sense to ask "am I moving?". Galileo's principle has the crucial implication that there is no scientific value in speaking of absolute space.

If space were absolute then we could imagine a giant mesh covering the whole Universe. Motion relative to the mesh would be "absolute motion."

But...we could choose another mesh, moving with constant velocity relative to the first mesh. Then things which were moving relative to the first mesh might not be moving relative to the second mesh.

There is no way of figuring out which mesh we should use. No special mesh means no absolute space.

This is Galileo's point.

#### Galileo's reasoning doesn't have anything to say about time.

Time is immutable according to Galileo. You can imagine little clocks at each and every point in the Universe, all synchronised to read the same time.

If two things happen at the same time according to one person then they happen at the same time according to everyone else....regardless of how they are moving.

<u>Aside</u>: If the two simultaneous happenings are very far apart then it might "look" like one happened before the other because light takes a finite time to travel to us from the events.

e.g. The Andromeda galaxy is over 2 million light years away from us. We are smart enough to realise that that means when we look at Andromeda today with our telescopes, we are seeing things which happened at the same time as events on the Earth over 2 million years ago.

#### Galileo restored a measure of democracy:

Think of carrying out an experiment on the platform of a train station. Now do the same experiment on a train moving through the station at constant velocity.

You'll get the same result in both cases.

But, if the train would be accelerating then that would mess things up...

So acceleration is special. People can tell they are accelerating.

#### A spanner in the works:

James Clerk Maxwell (1831-1879) wrote down a set of four equations that simultaneously described all of the laws of electricity and magnetism.

His equations predicted that light is a wave motion made up of oscillating electric and magnetic fields. The waves travel at a speed close to 300 million metres per second.

#### So what?

His equations stated that the speed of the waves is universal, i.e. everyone measures the *same* speed regardless of any motion.

So, either the speed of light is universal OR Maxwell's equations are wrong....



#### Universal speed is not common sense...

Common sense would say....

Imagine driving down the motorway at 60 mph. A car overtakes you at 90 mph. You say that the car travels away from you at a speed of 30 mph.

Now imagine a light wave travelling at 300 million metres per second. If you ran fast enough you could catch up with it.

That's the problem.... Everyone should see a different speed of light and so Maxwell's equations cannot really be correct.

Experiment: no evidence for any such variation in the laws of electricity and magnetism.

#### Enter Einstein....



"Maxwell's equations are correct"

The immediate implication is that you cannot even begin to catch up with a beam of light, no matter how hard you try.

This is <u>NOT</u> common sense...it is crazy and the implications are radical.

# Einstein was right!



The implications of following Einstein are: (a) Counter intuitive; (b) Bizarre. Midpoint of train

> Train Velocity

The observer says: "I see lightning striking both ends simultaneously!" Light rays from lightning strikes travel equal distances to the observer's eyes, and, therefore, arrive at their eyes simultaneously. The observer says: "I see lightning strike the front first and then the rear!"

The observer on the train is carried away from the spot where lightning struck the rear of the train. Therefore, the light ray from the rear has more distance to travel and arrives at the observer's eye later than the light ray from the front. During the train's forward movement the observer on the train is carried towards the spot where the lightning struck the front of the train. Therefore, the light ray from the front has less distance to travel to the observer's eye and arrives sooner than the light ray from the rear.

rain

#### So what?

Pre-Einstein: the person on the train would say that the lightning strikes still occurred simultateously.

"The difference in arrival times is just a consequence of the fact that I rush towards the light coming from the front and away from the light at the back....

But...and it is a massive but.....

They are NOT allowed to say "I rush away from light" or "I rush towards light".

For <u>both</u> observers the speed of light travels at the <u>same</u> speed (300 million metres per second).

The second observer is therefore <u>not</u> allowed to say: "the lightning really strikes both ends of the train at the same time." They <u>must</u> conclude that the lightning hit the front before it hit the back!

The implication is that what is simultaneous to one person need not be simultaneous to someone else.

This is very weird... it means that the notion of "at the same time" is subjective.

And it is NOT a trick of light...you can imagine that the lightning strikes hit clocks located at the site of the strikes, causing them to stop.

Clocks on the train at the front and back are stopped at different times.

Whilst two clocks at rest on the platform but still adjacent to the lightning strikes record the same time.

This immediately implies that time is <u>NOT</u> universal.

#### That means that clocks tick at different rates...

Imagine you are sitting in a carriage on the moving train. Suppose you send a beam of light on a roundtrip from the floor of the carriage to the roof and back. If the carriage is of height h then the time of the roundtrip is just 2h/c, e.g. 10 nanoseconds.

h

vt

Now, I am watching this from the platform. For me, the light travels on a <u>longer</u> triangular path.

Since I also see the light to travel at speed c it follows that I must conclude that the time for the roundtrip is longer than 2h/c. Even after correcting for the time it takes for the light to reach my eyes.... Think of the tiny clocks everywhere in space again.

We meet up later and compare notes. You say that your watch told you that the time taken for the roundtrip is 10 nanoseconds and I say that according to my watch the time taken was longer than that!

Hypoteneuse of triangle is of length  $\sqrt{h^2 + (\frac{Vt}{2})^2}$ 

h

vt

2

Pythagoras

where *t* is the time of the roundtrip, but

 $=\frac{2\sqrt{h^2+(\frac{\mathbf{v}t}{2})^2}}{2}$ 

time = distance / speed

Re-arranging this gives

$$t = \frac{2h}{c} / \sqrt{1 - \frac{v^2}{c^2}}$$

$$\gamma = 1 / \sqrt{1 - \frac{v^2}{c^2}}$$

#### This is a real effect..

If my wristwatch has registered a longer time interval than yours then it follows that my body clock has also registered a longer time than yours: I am older than you by virtue of the fact that I didn't go for a ride on the train!

There is an apparent paradox here.

Since the motion is relative, you could argue that it isn't really you who has travelled, it is I. So you should have aged more....not me. This is a good point.

The flaw is that for us to meet up again, you would need to change trains and come back. Doing that breaks the symmetry of the situation....I really do age more than you.

If I were to travel off at a speed of 75% the speed of light for 70 years (according to someone on Earth) how old would I be on my return?

$$\gamma = rac{1}{\sqrt{1-0.75^2}} = 1.512$$

So although an observer on Earth would age 70 years I would only age by 70/1.512 = 46.3 years.

NB: If speed is 1000 km/h then this effect is 1 millisecond

Implication: it is possible to travel to the most distance reaches in the Universe.....

The Andromeda galaxy is around 2.5 million light years away.

But an astronaut travelling at 99.99999999% speed of light could do the journey in 50 years according to on-board clocks.

If their children were part of a return expedition, a shocking 5 million years would have passed on their return to Earth.

Challenge is having the fuel to get to that speed.

Nowadays particle physicists routinely use Einstein's theory. The fact that an elementary particle has a lifetime dependent upon its speed is experienced on a daily basis.



AGS at Brookhaven

Sent muons around at 14m diameter ring and 99.94% speed of light.

A muon at rest dies in around 2 microseconds.

Pre-Einstein would expect it to manage around 15 laps of the AGS.

In reality they managed more like 400 laps.

#### Here is another weird thing....lengths change too.

Imagine travelling alongside one of those muons.

The muon now lives only 2 microseconds again.

So how come it still manages 400 laps?

Conclusion: the circumference of the ring must shrink from the perspective of you and the muon.

Consequence: you can fit a 4 metre car into a 3.9 metre garage.

Distances are subjective too....no universal space

Can't resist but also can't think of an easy way to explain why....  $E=mc^2$ Can't resist but also can't

Implication: mass and energy are interchangeable. Or, mass is just another form of energy (like heat or energy due to motion).

Mass is not conserved: stuff can disappear in exchange A 1kW fire burning for ~10 million years. A coal fire loses mass (tiny amount).

The energy from the Sun comes from this conversion of mass into energy (nuclear fusion). Sun loses 4 billion kilogrames of mass every second.

All energy is mass – a box of primed mousetraps weighs more than a box of triggered traps.

Back to the main narrative.....

Space & time are NOT universal... because lengths and time intervals change depending on how things move around.

Does something exist that is universal?

Yes.... "spacetime".

"Distances" in spacetime are not a matter of opinion...

Space & time blend into spacetime...

### How should we think of spacetime?

### Think of it like any other "space"



A map of Chicago = example of a space with Euclidean geometry

#### Except that spacetime is "curved"

Should not be such a shock to us. Since space and time are not immutable absolutes, i.e. they are malleable why shouldn't we question the geometry of spacetime?

This is not an unfamiliar concept....the surface of the Earth defines a curved (two-dimensional) space.





Spacetime is four-dimension, but it is not possible to even sketch a three-dimensional curved space, so these two-dimensional examples will have to suffice...



In the absence of gravity spacetime is "hyperbolic"

$$s^2 = (ct)^2 - x^2$$





# Einstein: 1915

# The existence of stuff causes spacetime to Warp... (no stuff = hyberbolic geometry)





Imagine throwing a ball from one side of the box to the other.

If the box is accelerating uniformly then the situation will be as in the middle picture.

Einstein realised that this situation should be *indistinguishable* from the case where the box is not accelerating but is instead in a uniform gravitational field (right hand picture).

Think of a freely falling lift. Did someone cut the wires holding the lift or did they turn off the gravitational field?

#### So in a sense we can always eliminate gravity....

.....by working in a frame of reference that accelerates just so as to cancel out its effect.

But only locally...after the freely falling frame has moved a bit it will not be suitable to cancel gravity at the new place (unless the gravity is the same everywhere).

It only works because everything falls with same acceleration in the presence of gravity.

There is a geometrical analogy with what happens on the Earth's surface....



We can think of local patches as being flat even though really it is spherical, e.g. parallel lines don't cross etc.

"The sum of flat patches = curved sphere"



We can think of local patches of spacetime as being "flat", i.e. no gravity locally.

The price to pay is that we must regard the space as being curved.

"The sum of flat patches = curved spacetime"

#### Einstein wrote a set of equations which replaced Newton's law of gravity.

$$R_{\mu
u}-rac{1}{2}g_{\mu
u}R=rac{8\pi G}{c^4}T_{\mu
u}$$

acceleration = G

The first test of these came with a measurement of the bending of light around the Sun in 1919:

> IX. A Determination of the Deflection of Light by the Sun's Gravitational Field, from Observations made at the Total Eclipse of May 29, 1919.

By Sir F. W. Dyson, F.R.S., Astronomer Royal, Prof. A. S. Eddington, F.R.S., and Mr. C. Davidson.

(Communicated by the Joint Permanent Eclipse Committee.)

Received October 30,-Read November 6, 1919.

[Plate 1.]

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Both of these point to the full deflection  $1'' \cdot 75$  of EINSTEIN's generalised relativity theory, the Sobral results definitely, and the Principe results perhaps with some un-

Philosophical Transactions of the Royal Society of London. Series A, Vol. 220 (1920)

### Einstein's theory worked and Newton's failed...



Pulsars: magnetised neutron stars. Essentially a giant nucleus.

Can measure the period of pulsars to remarkable precision, e.g.

# 0.059029997929613(7)s

Since they are very dense objects. The gravitational field in their vicinity is very strong = perfect arena to test Einstein's theory.

Double pulsar systems are rare but provide the best test to date....



Tests of General Relativity from Timing the Double Pulsar M. Kramer, *et al. Science* **314**, 97 (2006); DOI: 10.1126/science.1132305

### Tests of General Relativity from Timing the Double Pulsar

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The double pulsar system PSR J0737-3039A/B is unique in that both neutron stars are detectable as radio pulsars. They are also known to have much higher mean orbital velocities and accelerations than those of other binary pulsars. The system is therefore a good candidate for testing Einstein's theory of general relativity and alternative theories of gravity in the strong-field regime. We report on precision timing observations taken over the 2.5 years since its discovery and present four independent strong-field tests of general relativity. These tests use the theory-independent mass ratio of the two stars. By measuring relativistic corrections to the Keplerian description of the orbital motion, we find that the "post-Keplerian" parameter *s* agrees with the value predicted by general relativity within an uncertainty of 0.05%, the most precise test yet obtained. We also show that the transverse velocity of the system's center of mass is extremely small. Combined with the system's location near the Sun, this result suggests that future tests of gravitational theories with the double pulsar will supersede the best current solar system tests. It also implies that the second-born pulsar may not have formed through the core collapse of a helium star, as is usually assumed.

#### Using the 76 metre Lovell Telescope at Jodrell Bank

They can measure that the pulsars are getting closer together at a rate of 7mm per day.... Astonishing given that they are around 2000 light-years away from Earth.

# Without Einstein's General Theory of curved space-time GPS systems would not work

Clocks on satellites are used to "triangulate" locations. But the timing needs to be very accurate. (~ 20 ns)

The satellites are at altitudes of ~ 20,000 km where the gravitational field of the Earth is much less than at the surface of the Earth.

Clocks run faster in this environment and this needs correcting for (+45000 ns/day).

The satellites are also moving fast enough (14000 km/h) to need corrections from Special Relativity too (slow down by -7000 ns/day).

GPS would fail after a few minutes without these corrections

#### **Gravitational waves**

Just like "oscillating" electric charges induce radio waves so "oscillating" masses can induce gravity waves. Never been seen yet (because they are so weak). Although they are inferred from the double-pulsar measurements.

Tiny ripples in space-time.

Induce changes in length in objects as the wave passes.



Joint NASA/ESA project – launch ~ 2020

LISA will place three spacecraft in orbit around the Sun.

The three spacecraft will be 5 million km apart flying in a triangle formation.

When a gravitational wave passes by, these ripples in space gently push the spacecraft around.

The sensitive laser beams that connect the three spacecraft allow this tiny movement to be measured.

# The Big Bang

Einstein's theory admits the Big Bang as a possible solution. Space-time is a single dynamic entity.

Not right to think of material expanding into empty space.

Nor to ask where did the Big Bang happen.

Space itself is stretching as the Universe evolves: a bit like an expanding balloon.



#### Extra dimensions?

Why 3 space plus 1 time dimension?

String theory suggests 10+1 dimensions....

There is even the possibility that some of these dimensions could be "large" with us being "trapped" on a subspace.

We keep an open mind - need to think up a clever experiment.

#### The Big Challenge

Einstein forced us to re-visit the most basic ideas we have regarding space and time.

<u>There is a lesson</u>: it is not wise to extrapolate experience beyond its realm. Why should the physics of fast moving objects be the same as the physics of slow moving things? Why should the physics of very massive objects be the same as the physics of light objects?

Why should the physics of very tiny things be the same as the physics of large things....this is the realm of the QUANTUM THEORY....

<u>Today</u>, Einstein's Theory cannot be meshed with Quantum Theory. Either one or both must be revised. Does spacetime "break up" at tiny distance scales? Are the fundamental objects in Nature tiny vibrations of energy known as strings? Or something else?