GRAVITY

What was known in Einstein's day?

What keeps your feet on the ground? Gravity, of course. But what exactly is it?

Why things fall towards the Earth and why our feet stay on the ground has kept thinkers and scientists busy for hundreds of years. One of the earliest ideas came from the Ancient Greek philosopher Aristotle. He believed that Earth was at the centre of the universe and that everything in the universe was made up of four elements – earth, water, air and fire. He thought that these elements moved towards their natural place and because earth was the heaviest it settled at the centre, with water in a ring around it, then air and finally fire. Outside these rings of elements sits a final fifth element – a mysterious 'aether' – that fills space. It was an interesting theory... but we now know that it wasn't correct.

THE HAMMER AND THE FEATHER

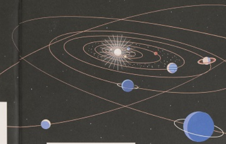
After Aristotle, the next great thoughts on gravity came from the Italian Galileo Galilei in around 1590. Galileo is famous for testing his theories by dropping balls of different weights from the top of the Leaning Tower of Pisa. It is a fun story, but probably not actually true. In fact, he carefully rolled balls of different weights down a slope and measured their speed. He proved Aristotle wrong, discovering that falling objects, no matter what their weight or mass, would accelerate at the same speed because of the force of gravity.

That means that a heavy object such as a hammer and a light one such as a feather dropped simultaneously from the same height would hit the ground together!

If you actually try this yourself, though, the feather will probably take longer to hit the ground, because (as Galileo realised) the feather will be slowed down by air resistance.

But almost 400 years later, when astronauts went to the Moon on the Apollo 15 mission in 1971, they conducted Galileo's experiment. Commander David Scott dropped a hammer and a falcon feather from the same height.

Although the feather weighed a lot less than the hammer, they both fell at the same speed and reached the ground at the same time because there was no air resistance.



THE FALLING APPLE

Just over 200 years before Einstein came up with his theory of relativity, the British scientist Isaac Newton wrote one of the most important books explaining how the universe works. Published on 5 July 1687, his book was called *Philosophiae Naturalis Principia Mathematica* (or the Principia for short). Newton's ideas were so important that they became the foundation for what is now called 'classical mechanics', which are rules that describe the movement of all objects in the universe.

Newton is supposed to have discovered gravity while sitting under a tree, thinking about the universe. Suddenly, an apple fell and hit him on the head. Why, he wondered, do apples always fall straight down to the ground?

To explain why, Newton created his law of universal gravitation, which explains why any two objects in the universe are attracted to each other.

Newton wrote: 'The forces which keep the planets in their orbs must [be] reciprocally as the squares of their distances from the centres about which they revolve: and thereby compared the force requisite to keep the Moon in her Orb with the force of gravity at the surface of the Earth.'

LESS MASS = LESS FORCE

MORE MASS = GREATER FORCE

Newton had discovered that every mass exerts a gravitational force on every other mass. The higher the mass of two objects, the stronger the gravitational force between them. Conversely, the greater the distance between two objects, the weaker the gravitational force.

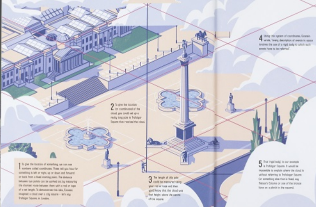
Incredibly, his theory was used to successfully predict the existence of the planet Neptune based on the movement of the planet Uranus. But there was a problem: his theory could not explain the strange orbit of the planet Mercury. That would have to wait until Einstein developed his theory of relativity, which improved on Newton's ideas.

SPACE

What was known in Einstein's day?

Where are you? Can you describe where you are, without referring to the things around you? Give it a go.

Just like gravity and time, space was an idea that scientists and thinkers had been puzzling over for centuries. By the time Einstein was working on his theory of relativity, there were some well-known ideas about geometry, which literally means 'to measure the earth', and is about the size and position of things relative to each other and the shapes they make.



1 To give the location of something, we can use numbers called coordinates. These tell you how far something is left or right, up or down and forward or back from a fixed starting point. The distance between two points can be worked out by measuring the shortest route between them with a rod or tape of a set length. To demonstrate this idea, Einstein imagined a cloud over a city square – let's say Trafalgar Square, in London.

2 To give the location (or coordinates) of the cloud, you could set up a really long pole in Trafalgar Square that reached the cloud.

3 The length of this pole could be measured using your rod or tape and then you'd know that the cloud was that height above the centre of the square.

4 Using this system of coordinates, Einstein wrote, "every description of events in space involves the use of a rigid body to which such events have to be referred".

5 That 'rigid body' in our example is Trafalgar Square. It would be impossible to explain where the cloud is without referring to Trafalgar Square (or something else that is fixed, say Nelson's Column or one of the bronze lions on a plinth in the square).

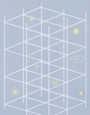
"A human being is a part of the whole, called by us 'Universe', a part limited in time and space."
– Einstein

ABSOLUTE SPACE

Although the idea of absolute space (like absolute time) was suggested by Aristotle, Isaac Newton was the first person to set down the idea in clear terms. Immediately after declaring in his *Principia* that "Absolute, true and mathematical time, of itself and from its own nature, flows equably without relation to anything external", he wrote: "Absolute space, in its own nature, without relation to anything external, remains always similar and immovable."

The idea was that you could divide up the world – and beyond that the universe – into a grid, laying rods of the same length end to end in all directions. That way you could measure off all space and the distances would always stay the same no matter what you did, where you went or how fast you travelled.

This seems sensible. If you set out some chairs in a room and measure between them, the distances don't change (unless you rearrange the chairs). But – as with time – Einstein would go on to show that this wasn't true!

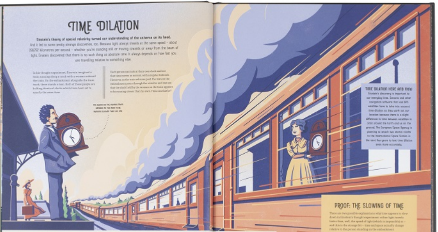


TIME DILATION

Einstein's theory of special relativity turned our understanding of the universe on its head. And it led to some pretty strange discoveries, too. Because light always travels at the same speed – about 299,792 kilometres per second – whether you're standing still or moving towards or away from the beam of light, Einstein discovered that there is no such thing as absolute time. It always depends on how fast you are travelling relative to something else.

In his thought experiment, Einstein imagined a train running along a track with a woman onboard the train. On the embankment alongside the train track, there stands a man. Both of these people are holding identical clocks which have been set to exactly the same time.

Each person can look at their own clock and see that time moves as normal, with a regular ticktock. However, as the train whizzes past, the man on the embankment peers through the window and can see that the clock held by the woman on the train appears to be running slower than his own. How can that be?



1 Imagine that, rather than a normal clock, there is a pair of mirrors exactly 299,792 kilometres apart, with a pulse of light bouncing between them. We know that the light will take exactly one second to travel from one mirror to the other because it travels 299,792 kilometres per second.

2 Now, if the train travels at half the speed of light, the bouncing pulse in the clock on the train, as seen by the man on the embankment, appears not to go up and down, but to follow a diagonal path as the mirrors move with the train.

3 The light leaves the bottom mirror but as it travels upwards towards the top mirror the mirrors have moved forwards with the train. That means the light has to travel diagonally forwards to meet the top mirror and so travels a greater distance between the two mirrors if viewed by someone who is standing still relative to the train.

TIME DILATION HERE AND NOW

Einstein's discovery is important to our everyday lives. Satnavs and other navigation software that use GPS satellites have to take into account time dilation as they work out our location because there is a slight difference in time between satellites in orbit around the Earth and us on the ground. The European Space Agency is planning to attach two atomic clocks to the International Space Station in the next few years to test time dilation even more accurately.

PROOF: THE SLOWING OF TIME

There are two possible explanations why time appears to slow down in Einstein's thought experiment: either light travels faster than, well, the speed of light (which is impossible) or – and this is the strange bit – time and space actually change relative to the person standing on the embankment.

The result is called 'time dilation': time actually slows down the faster you travel.

This strange discovery has been proven many times using very accurate atomic clocks, comparing one on the ground with another onboard an aircraft. In Germany, in 2014, one of the most accurate tests was conducted using high-speed particles. Scientists used lithium ions as moving clocks and accelerated them to one third the speed of light. The result was that the fast-moving particles aged less than the slower ones.

THE SHAPE OF THE UNIVERSE

'The idea of a straight line also loses its meaning.' – Einstein in Relativity

CURVED SPACE-TIME

The universe, Einstein had discovered, was not just a big, empty space dotted with stars and planets but curved and warped by gravity. In fact, gravity is the curving of space-time.

One of the best ways to imagine this is to think of space as a very large trampoline. If you put a really heavy bowling ball in the middle of the trampoline, it curves the surface. Now, roll a small tennis or ping pong ball across the trampoline and it will roll towards the bowling ball.

The larger the mass – whether it's a bowling ball on the trampoline or a star like our Sun in space – the more it will distort the space-time around it. If you placed several balls of different masses on the trampoline they would produce a rippled, warped surface. This gives you an idea of what our universe looks like.

GETTING FROM A TO B

Draw two dots on a flat sheet of paper. What is the shortest path between them? A straight line, of course.

In classical physics, the maths to explain this is called Euclidean geometry, named after an Ancient Greek mathematician called Euclid.

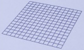
We can use this kind of geometry to work out distances on maps and the angles at the corners of a triangle, for example. But in four-dimensional space-time, things get a little bit more complicated!

In Euclidean geometry, you need just three coordinates to locate something – x, y and z. But in the non-Euclidean geometry of a curved space-time, where the shortest path between two points is not a straight line, but a curve, Einstein found that to work out distances he needed to solve 10 equations for every coordinate.

WHAT SHAPE IS THE UNIVERSE?

Einstein worked out that the universe is "finite and yet has no limits". How can that be?

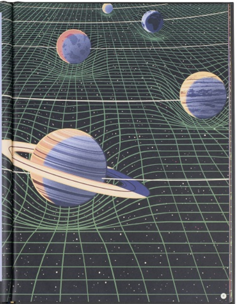
Imagine you're on a flat planet and can go in any direction. What happens when you get to the edge? You'd fall off!

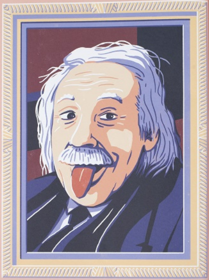


Now, roll that flat land up into a ball. You can still roam anywhere you like, but while it still seems flat it actually curves very gently, so if you were to walk far enough in one direction you'd return to where you started.

The universe is the same – but curved in four dimensions. You could travel forever in any direction and never reach the edge of the universe, but eventually return to where you started.

What's more, the universe is actually expanding, with every point in space moving away from every other point in space.





EINSTEIN THE CELEBRITY

"When a blind beetle crawls over the surface of a curved branch, it doesn't notice that the track it has covered is indeed curved. I was lucky enough to notice what the beetle didn't notice."
– Einstein explaining his fame to his son, Eduard

Just a year after the end of the First World War, in which the Germans had been fighting the British and French, an English scientist had proved that an incredible theory dreamed up by a German Jew was correct. It was just the news that the world needed.

AN OVERNIGHT SUCCESS

Einstein's discovery caught the imagination of people all around the world when it was proved by Arthur Eddington's expedition to watch the solar eclipse in 1919 – even if they didn't really understand the theory.

Newspaper headlines celebrated Einstein's discovery:

"LIGHTS ALL ASKEW IN THE HEAVENS
Men of Science More or Less Agog Over Results of Eclipse Observations."
– New York Times

THE MAD PROFESSOR

Part of Einstein's appeal was the way he looked.

His wild, curly hair and slightly dishevelled clothes, as well as his complex theories and desire to try to explain his ideas to ordinary people in addition to scientists, meant that he became instantly recognisable wherever he went.

In fact, the almost cartoonish image we have of a genius scientist today is based on Einstein.

At a time when there were very few celebrities, Einstein welcomed the attention and was photographed and interviewed everywhere he went. On a trip to America in 1931, Einstein and his wife Elsa met the actor Charlie Chaplin who invited them to the premiere of his new film, *City Lights*. They were photographed together – the most famous physicist in the world beside the most famous actor in the world.

Over the years, Einstein was interviewed many times and had his photograph taken regularly – including one that has been printed on T-shirts and posters of him sticking out his tongue!

EINSTEIN'S BRAIN

What is genius and where does it come from?

When Albert Einstein died in 1955, aged 76, a very strange thing happened. Thomas Harvey, a doctor at Princeton Medical Center where Einstein died, secretly removed the scientist's brain before he was cremated!

Because Einstein had become the image of the absent-minded, crazy-haired genius, Dr. Harvey wanted to know if he could find the source of genius by looking at Einstein's brain. So, without permission, he removed the brain to study it.

Harvey weighed the brain (1,230g) and dissected it into 170 pieces, before carefully storing them in two large jars in an old, wooden cider crate. Then the brain was forgotten for more than 20 years until it was rediscovered in 1978.

It wasn't until 1999 that any real discoveries were made about Einstein's brain, published in a paper called 'The Exceptional Brain of Albert Einstein' by neuropsychologist Sandra Witelson. By then, it was being studied at McMaster University in Canada and Witelson discovered that his brain had some differences in the way it looked compared to other people's brains.

But we still don't know whether these differences led him to be a genius.