THE REST IS NOISE

Einstein's Theory of General Relativity

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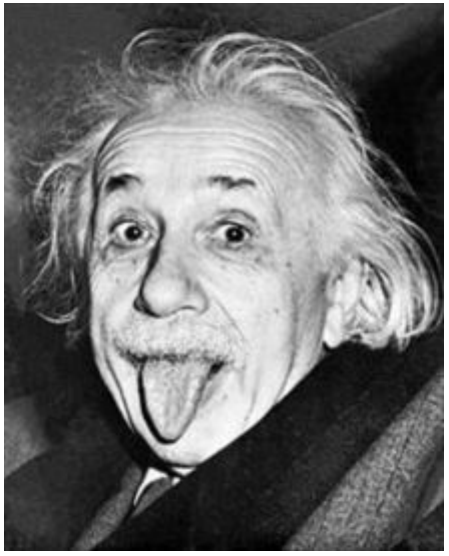
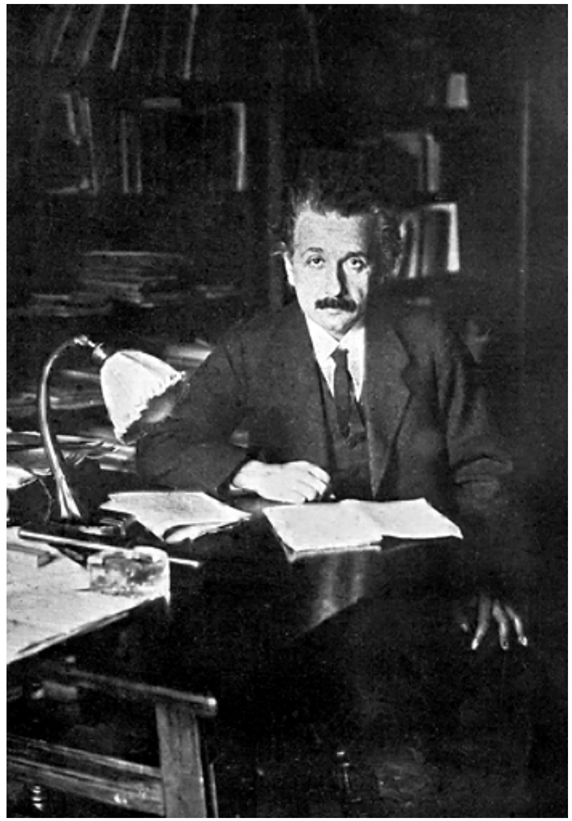


This is an annotated version of the talk. Anything contained in a box, like this, is supposed be close to what I said.

This talk was aimed at arts and music folk at a festival in the South Bank Centre, London. The main purpose was to get across the basic ideas of general relativity. But I also touched upon the impact of the theory, both on Einstein's own life and on a broader cultural level.

1915: Einstein's General Relativity



General relativity is the theory of gravity

I’ll start with the punchline. If you take only one thing away from this talk, this should be it:

General relativity is a theory of gravity. In fact, it is *the* theory of gravity. It's almost one hundred years since its discovery and we have nothing better to replace it. On small domestic scales, it is the theory which explains why apples fall from trees, why I return to the stage when I jump, and why you're all stuck to your chairs. But it really comes into its own when we think big. It explains why the moon orbits the Earth and why the Earth orbits the Sun and why the Sun is one of a 100 billion stars orbiting a huge black hole that sits at the centre of our Milky Way galaxy and why our galaxy is one of a 100 billion spread throughout space, all moving inexorably apart as the Universe expands. It is the theory that governs the dynamics of cosmos on the grandest scales imaginable.

Einstein discovered General Relativity in 1915. There don’t seem to be any pictures from the year of discovery; this one was taken a few years later. In 1915, Einstein was 36 years old. He didn't yet have the celebrity status that he would later. His name wasn’t known to the man on the street. But, at least in scientific circles, he was a superstar. He had just been hired to Berlin where he held the most prestigious position in Europe, he was youngest member of the Prussian Academy, he’d made many important contributions to science. But his general theory of relativity, which was still to come, was by far his greatest achievement. In fact, it remains one of the greatest achievements in the history of science.

I'd first like to tell you why Einstein was thinking about gravity. To do so, I need to take you back in time. In fact, I'm going to take you back in time twice: first just 10 years to 1905. And then back more than 200 years.

1905: Einstein's Special Relativity

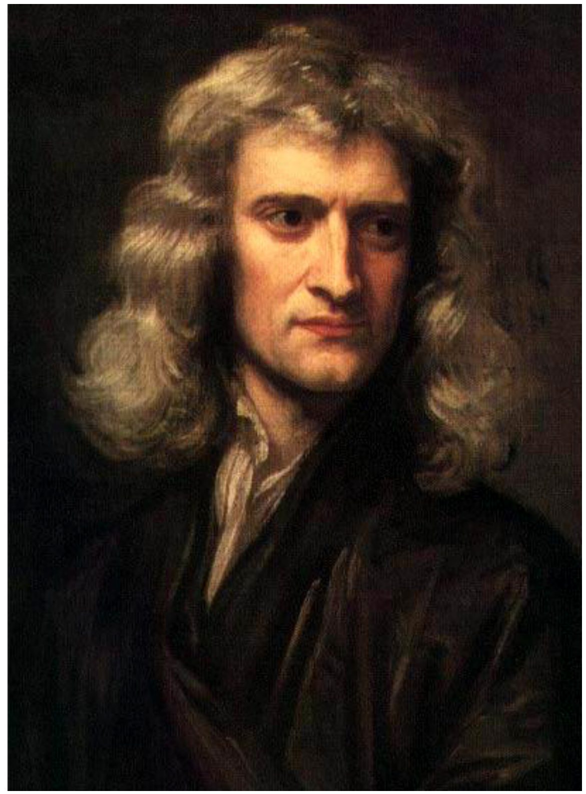
Nothing travels faster than light…

This is Einstein in 1905. I think it's fair to say that Einstein was a cocky young man. At the time, he didn't have a position in a university, he didn't even have a PhD. And the main reason was simply that he'd manage to piss off every scientist he ever met, usually with some combination of arrogance, laziness and rudeness. So in 1905 he was working as a civil servant in Switzerland, on the lowest rung of the ladder as a junior patent clerk in Bern. The good thing about this job was that it was easy. It really didn't tax Einstein at all and left him with lots of spare time to think about science. And in that year he did something that has never happened before or since. He wrote 4 papers. One of these was simply a very good paper and finally won him a PhD. But the other 3 were on a different level: each of them revolutionised an area of science.

For this talk, the most important paper was on *special relativity*. The word special here doesn't mean "kind of fancy". It means “specialised”; it's a theory which only works in a limited number of situations. As opposed the "general" theory which is all encompassing and would eventually subsume the special theory within it. The special theory is where the famous E=mc^2 comes from. The essence of the theory is the following: there is a speed limit in our Universe. The laws of physics conspire so that nothing can ever travel faster than the speed of light.

We don't notice this restriction in our everyday lives simply because the speed of light is really fast. To give you some idea, the speed of sound is pretty fast. It's around 700 mph. But we can build airplanes that go faster than the speed in sound. In contrast, the speed of light is around 700 million miles per hour. We're nowhere close that.

1687: Newton's Theory of Gravity



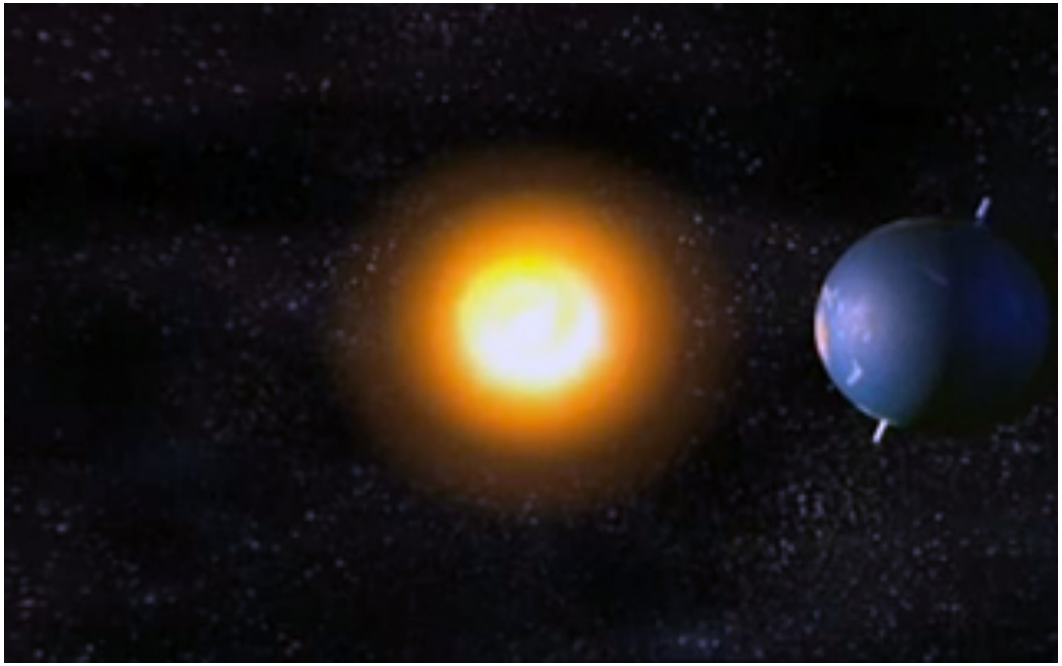
Why the apple falls from the tree…

The second piece of history that I need to tell you about is from 200 years earlier. In 1687, Newton published his own masterpiece, a book called the *Principia*. This was really the beginning of modern science. The Principia contains many important things, but among them is a theory of gravity. Newton wrote down a mathematical equation that describes how gravity works. It tells us how apples fall from trees and how the moon goes around the Earth and, most importantly, why these two seemingly different things are actually have the same underlying cause: gravity.

Newton's theory had lasted more than 200 years. But Einstein was puzzled. He couldn't see how Newton's theory of gravity and his own theory of the speed of light could both be correct. One of them had to be wrong. And, as I said, Einstein was a cocky young man. He was pretty sure that it was Newton who would turn out to be wrong.

This is what puzzled Einstein.

How Fast Does Gravity Move?



The Earth goes around the Sun. It goes around once a year and it travels, more or less, in a circle. Now, the Sun’s a long way away. It's so far, that it light takes 8 minutes to travel from the Sun to the Earth. So the Sun we're seeing in the sky isn't the Sun as it is now, but it's the Sun as it was 8 minutes ago. Because that's how long the light took to reach us.

Now suppose the Sun was to one day explode. What would we feel? Well, we wouldn’t know about it straight away. For 8 glorious minutes, we'd be sitting here quite happily as the light from the Sun streamed towards us. We’d be completely oblivious to the terrible thing that was about to happen.

But what about gravity? The Earth moves in a circle around the Sun. But, if the Sun wasn't there, there’s no reason for it to move in a circle. It would just keep going in a straight line. So this was Einstein's puzzle: when does the Earth stop moving in a circle and start going in a straight line? Does it happen straight away or does the Earth continue to move in a circle for 8 minutes or so after the Sun explodes before shooting off in a straight line?

In case it's not obvious, I should point out that Einstein was not a pragmatic man. The Sun's exploding and all he's worried about whether the Earth travels in a straight line or not. But this was how he did science. He would cook up these childish little scenarios in his head and just push them to the limit. He'd try to find some contradiction and when there was something that didn't make sense, that's what he'd focus on.

Now the trouble was that according to Newton's theory, the Earth should know immediately that the Sun had disappeared. But Einstein said that couldn't be right. Because, according to him, nothing can travel faster than the speed of light....not even the effect of gravity. So Einstein was convinced that it must be the case that the Earth continues to move in a circle for at least 8 minutes.

Einstein thought…

…he thought for 8 years

So Einstein thought. At first he just tried to see if there was some way he could tinker with Newton's equations, some simple way to delay the effect of gravity reaching the Earth. But he couldn't find any way to do it.

In 1907, Einstein started thinking deeply about gravity. He went right back to basics, trying to figure out what's going on. And it took him 8 years to get to the final answer. For the first 4 of these he was doing other things, but from pretty much 1911 onwards he was thinking only about these questions of gravity.

I should also mention that he was the only person in the world who cared about this. This was an exciting time in physics. The basics of atomic structure were being uncovered, it was the early days of quantum mechanics. And Einstein was at the forefront of all these developments. But what he really cared about was this stupid question of whether the Earth continues to move around the Sun after it explodes.

The story of how Einstein discovered general relativity is like something from a Hollywood movie. He first thought he'd cracked it in 1913. He came up with what he called an "outline" of the theory. He realised it wasn't perfect, but he thought it was basically right and just needed a little polishing. So for two years, he tried to fix it up. But, somehow, he just couldn't quite do it. And slowly, over time, some nagging doubts start to creep in. Things came to a head in the summer of 1915 when he went to the German town of Gottingen to give a series of lectures on his theory. In Gottingen, there was a guy called David Hilbert. And David Hilbert was recognised as the greatest living mathematician at that time. Einstein spends a week there and Hilbert takes a great interest in what he has to say.

Then Einstein returns to Berlin and two things happen. First, he realises that his theory is completely rubbish. The basic ideas were right but this whole framework that he's constructed is just wrong. It doesn't work. Secondly, he gets a letter from Hilbert saying "Well I really liked your lectures, but I'm not really sure it's right. So I've decided to work on this myself".

After 8 years of working on his own, suddenly Einstein has competition: the worlds best mathematician is hot on his heels in a race to discover general relativity.

At first Einstein gets kind of depressed that he's wasted 2 years of work. But then he buckles down and he focusses everything on this problem. He works on this for months, sometimes forgetting to eat or to sleep.

Finally it gets to November 1915 and Einstein has to give a series of 4 lectures -- one a week -- on General Relativity to the Prussian academy, to all the brightest scientists in Berlin. He'd agreed to do this way back when he still thought that he knew what he was talking about. But now he doesn't have a theory. He manages to get together enough material to give the first lecture. And, from then on, he’s working in real time. During the week, he spends his time trying to solve this problem that he's struggled with for 8 years. And, at the end of each week he stands up and gives a lecture on what he’s just figured out. Meanwhile, Hilbert's breathing down his neck sending him letters which show that he's also on more or less the right track. Finally, in the week before his last lecture, he cracks it. And once he's got it, it's so beautiful that it's just obvious that it's right. At the end of the week, he stands up at the Prussian academy and announces to the world the theory of general relativity that he figured out 48 hours earlier.

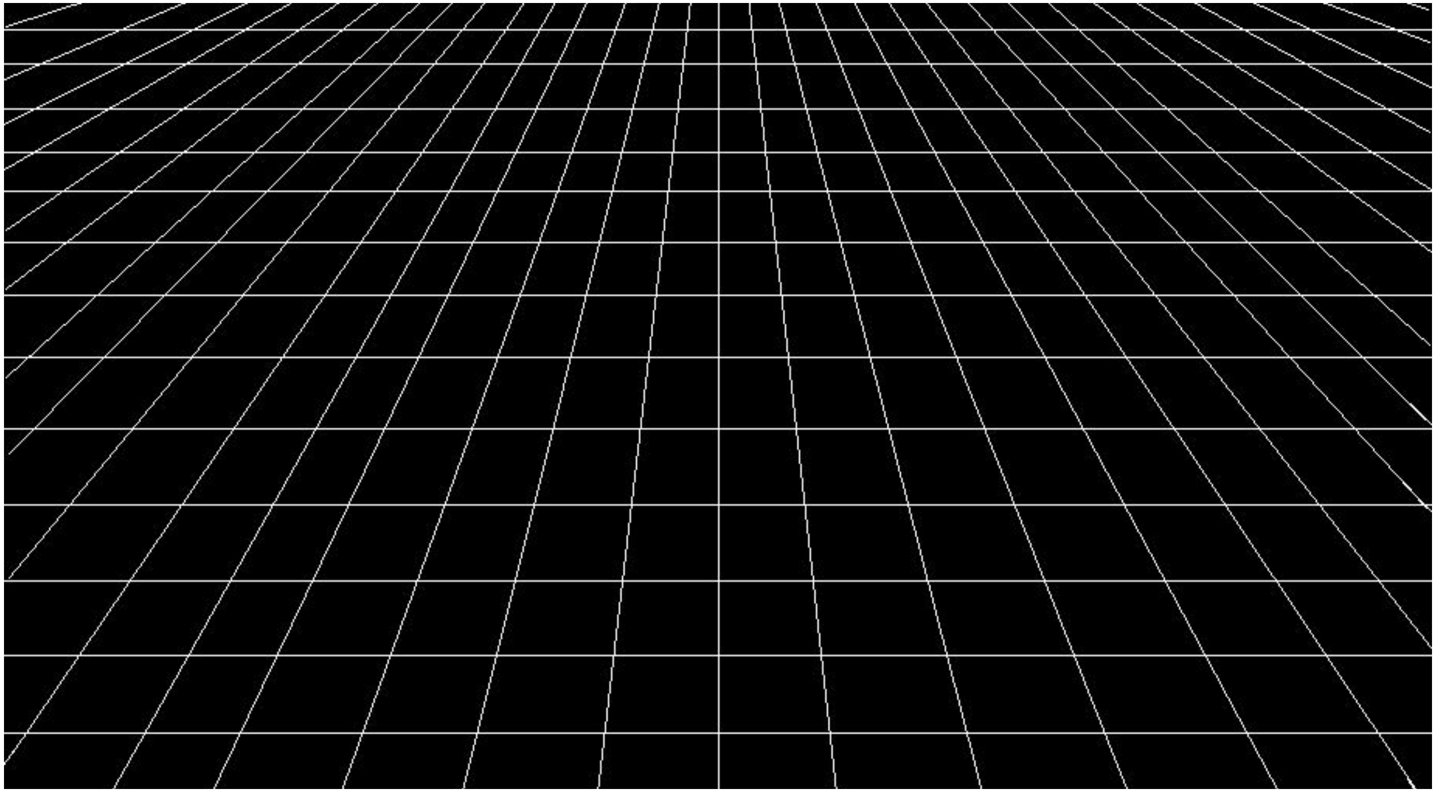
And this is what he told them.

$$R_{\mu\nu} - \frac{1}{2} R \, g_{\mu\nu} = \frac{8\pi G}{c^4} \, T_{\mu\nu}$$

You've probably heard of E=mc^2 -- that was also due to Einstein. But this is Einstein's real masterpiece. This is his equation which is so breathtaking it makes the hairs on the back of your neck stand up. This is the most beautiful book you've ever read or the most wonderful song you've ever heard, all rolled up into a little piece of mathematics.

Let me tell you what it means.

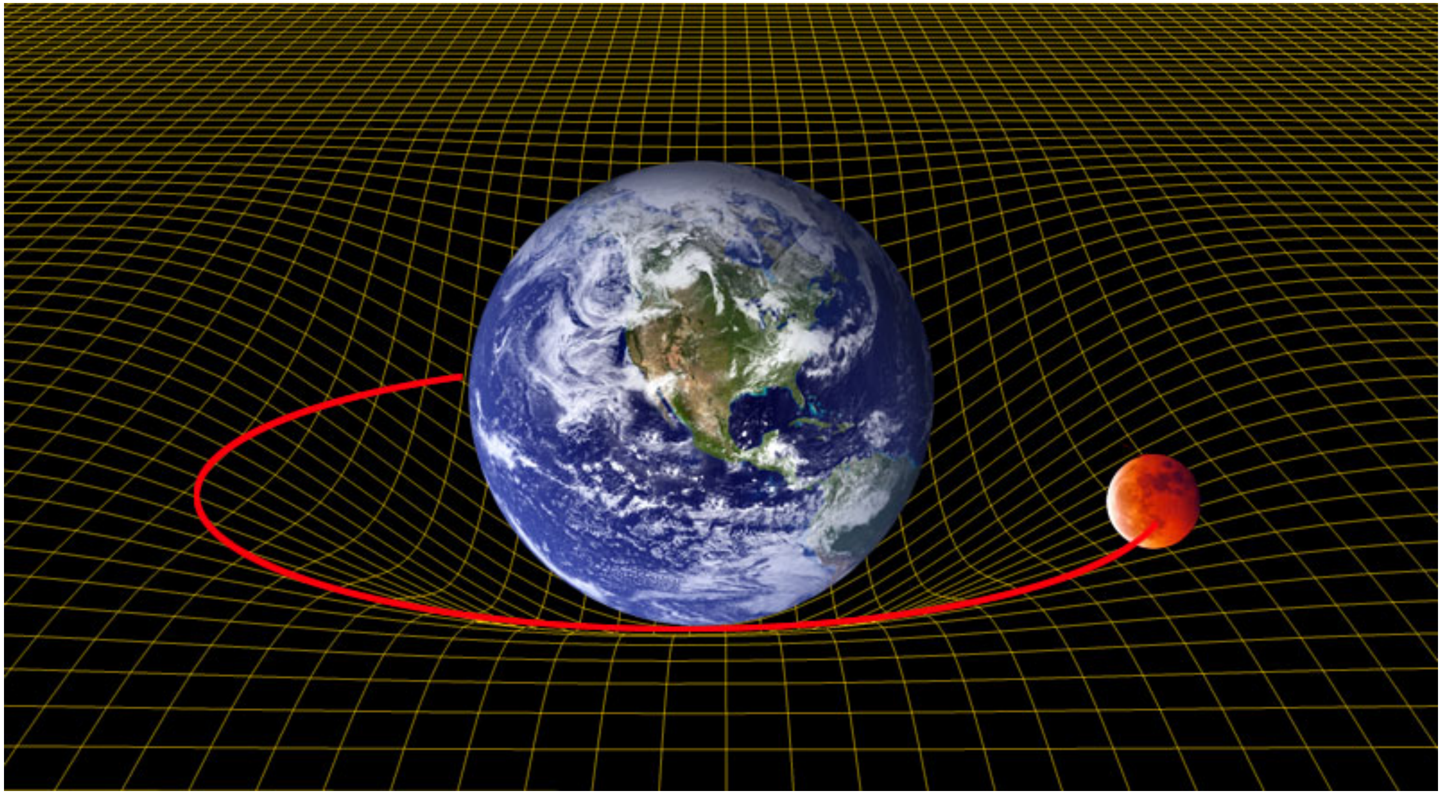
This is empty space



This is empty space. A space with nothing in it at all. Before Einstein, we were used to thinking of space as stage on which the laws of physics play out. We could throw in some stars or some planets and they would move around on this stage.

Einstein realised that space isn't some passive stage. Instead space itself is dynamic. It responds to what's happening within it.

Heavy Stuff Makes Space Bend



The moon orbiting the Earth

If you put something heavy in space -- let's say a planet like Earth -- then space around it gives a little. The presence of the planet causes a small dent in space -- and in fact, in time as well.

And when something else moves close to the planet --- say the moon --- it feels this dent in space and it rolls around the planet like a marble rolling in a bowl. This is what we call gravity.

The old idea of Newton – that there's a gravitational pull between two objects – is not correct. The thing that we call the force of gravity is due to the space and time in which we live warping and bending and causing other nearby objects to fall towards it.

Now this sounds like something you'd see in Star Trek. But it's not. It's the way our Universe works. This dance of the cosmos, as galaxies orbit and spiral, is a dance between matter and spacetime itself. Stars and planets move, causing space to bend in their wake, causing other stars and planets to move, causing space to bend in their wake. And so on. This is Einstein's great insight. This is gravity.

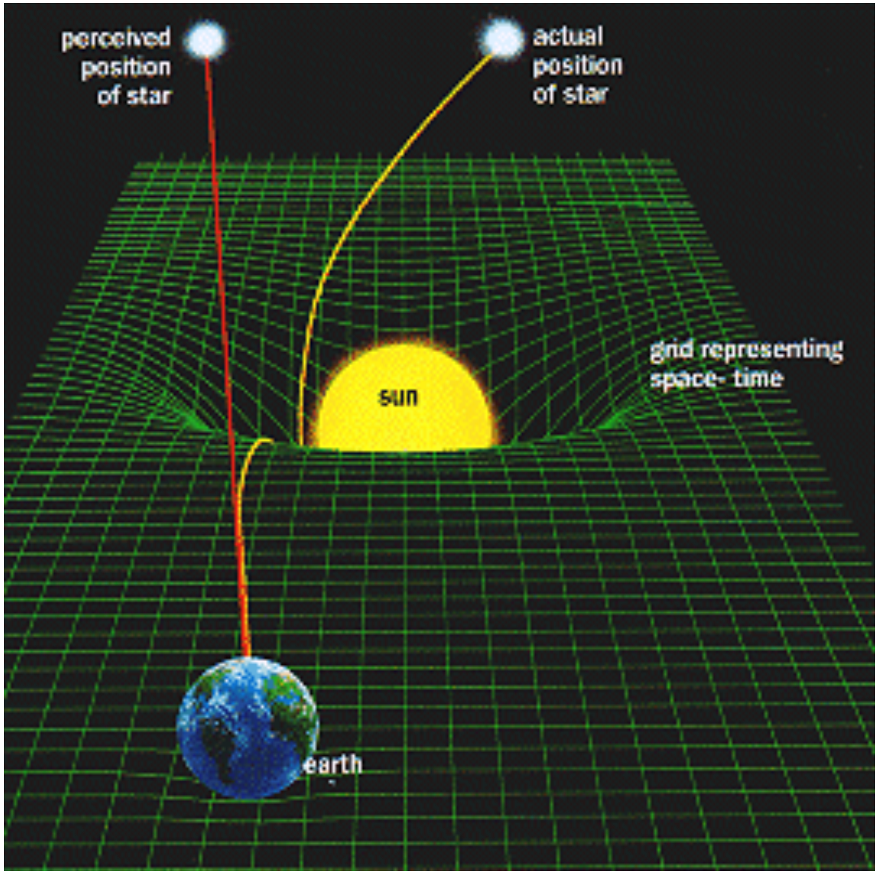
Gravity is the manifestation of
the curvature of space and time

How do we know it’s right?

So maybe all of this sounds wonderful to you or maybe it sounds preposterous. But the great thing about science is that you don't get to just make up fantasy stories, no matter how compelling, and have people accept them. We need some evidence. So how to do we know it's true?

Well, Einstein's new theory of gravity made a number of important predictions that Newton's theory didn't. I'll mention a few more at the end of the talk, but for now there's one that's most important: it's that light bends

Einstein's Prediction: Light Bending



This is the idea. Suppose that there's a star hidden behind the Sun. You might think that the light from the Star can't get to us because the Sun is in the way. But Einstein realised that this wasn't the case. According to his theory, because there's an indentation in space, light doesn't have to travel in a straight line. It can head out at some angle, bend around the Sun, and then come to hit our eyes.

But when we trace the light ray back in a straight line, we would see the star sitting a little to the left of the Sun rather than behind the Sun. So we'd think that the position of the star was a little different from its actual position.

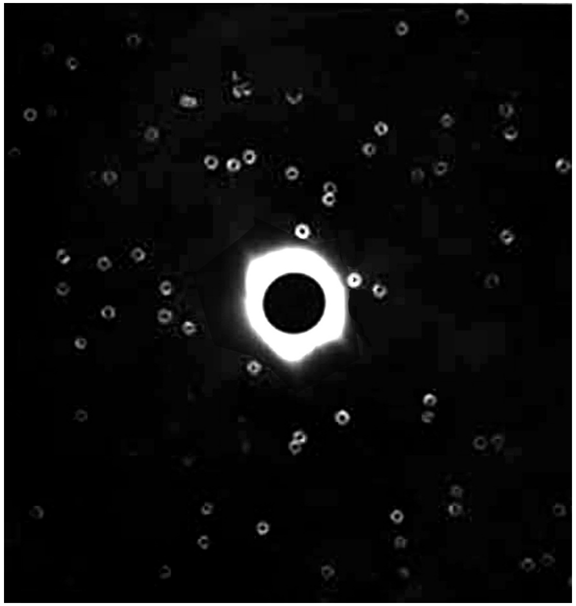
This then was Einstein's prediction. When the Sun is front of stars, their position in the sky gets shifted by some small amount compared to when the Sun isn't in the way.

But there was a problem with this. Which you may have noticed. It's that when the Sun's out, you don't get to see the stars. Because when the Sun’s out, it's day time. And the stars come out at night. The reason you don't see them in the day is just because the Sun's too bright. And that's especially true of the stars that are directly behind the Sun.

Except there's one very special circumstance when we can see the stars behind the Sun. And that's during a full eclipse. By some random coincidence, the size of the moon in the sky is exactly the same as the size of the Sun and every few years the moon passes between the Earth and Sun and blocks the Sun completely. It's spectacular when it happens. And for just a few minutes, you can use telescopes to see the stars behind the Sun. And you get to test Einstein's theory.

Light Bending

Light bending in 1919



Light bending in 2009

The first test of Einstein's theory was performed in 1919 by a British astronomer called Arthur Eddington. They set out on two expeditions: one to the west coast of Africa, the other to Brazil. They waited for the eclipse, prayed it wasn't cloudy, and took pictures of the stars behind the Sun. This was the picture that they took: you can see the Sun in the middle, blackened out by the moon. And the stars around. And when they measured the positions of the stars they found that they had shifted by exactly the amount predicted by Einstein.

Here's a more modern view of this light bending. This was taken in 2009 by the extraordinary Hubble telescope. It's not looking at the Sun but instead deep into space. And this bright glowing ball in the top right corner is a galaxy, made of about 100 billion stars. But behind this galaxy, at about twice the distance, is another galaxy. It's obscured by the first. But the light bends around in such a way that you can see it. But because the light can bend in any direction, what you actually see is this smeared curve. This line is really a dot positioned exactly behind this one, its light bend because of warps in space and time.

Einstein the Celebrity

LIGHTS ALL ASKEW IN THE HEAVENS

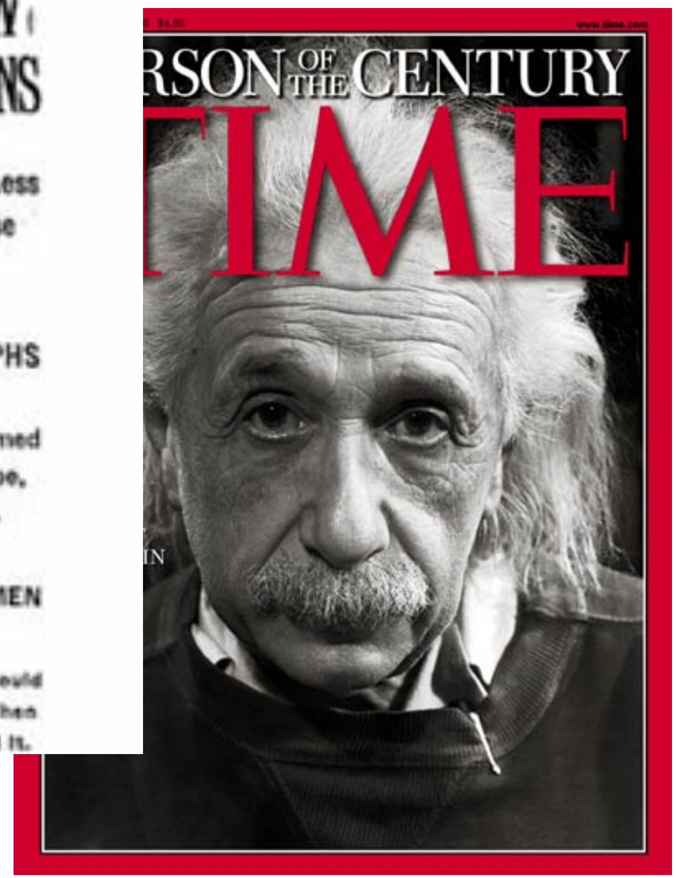
Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.



The eclipse measurements propelled Einstein to superstardom. In part it was because the war had just finished and here was a great story about an English astronomer confirming a German scientist's theory. But it was big news. It made the front page of the New York Times every day for a week. Here's one of their rather charming headlines. Anyone remotely famous --- politicians, actors -- were all being asked whether they understood the theory of relativity. All of them said they had no idea what it was but they were sure it was important.

For the most part, Einstein loved all this publicity. He was great with pithy little quotes to the press. He had this iconic look. They loved him. But fame had its downside. Because Einstein was by far the most famous public intellectual in the world. He lived in Berlin. And he was Jewish. And being a prominent public Jewish intellectual in Berlin after the war was not the easiest life.

On the most extreme occasions, the police advised Einstein to leave town due to concerns about his safety. But there was also growing anti-semitism within the scientific establishment in Germany. There was an astonishing idea that Germans should focus on “Deutsche Physik" instead of Jewish physics, where Jewish physics meant relativity. There were conferences organised against relativity, really pure anti-semitism but wrapped up in scientific language to try to argue that this theory was controversial. And it had an effect. It's very easy for vocal people to shout loudly and muddy the scientific waters.

One arena in which this showed up was the Nobel prize. It was completely clear that Einstein should win. But there was at least one Nobel laureate on this anti-semitic crusade and the muddy waters extended to the Nobel prize committee. Finally, in 1921 and it reached the stage where if you didn't give the prize to Einstein, you couldn't give it to anyone. So, incredibly, they chose not to give to it anyone. Finally, in 1922 – presumably because the problem hadn’t gone away -- they managed to, rather belatedly, see reason and they awarded a back-dated 1921 Nobel prize to Einstein. Even then, they didn't award it for general relativity. They gave it for his other achievements. To this day, general relativity has never won a Nobel prize.

Einstein didn't turn up for the ceremony.

Einstein and the Rise of Nationalism

"I am, as a human being, an opponent of nationalism. But as a Jew, I am from today a supporter of the Zionist effort."

Einstein, 1919

This rise of German nationalism caused a reaction in Einstein: it pushed him towards his Jewish roots. He'd never really considered himself Jewish before. He was atheist from an early age, a position he more or less kept throughout his life. But during the war, he started to identify very strongly with Jewish culture and the cause of Zionism. This was Einstein's own rise of nationalism. Towards the end of his life, he was even offered the presidency of Israel. But he turned it down, saying that he'd prefer to just keep working on physics. As usual he had a cute way of phrasing it: politics is for today, an equation is forever.

Relativity and Culture

I want to finish by telling you a little about the legacy of relativity. And part of this is how it fits within the broader cultural landscape. In the early twentieth century there was an explosion of creativity in all areas of the arts, from the cubism movement of Picasso and Braques, in music the development of atonality by Schoenberg, in literature the long tedious passages of James Joyce, you could even throw the psycho-analysis of Freud into the mix as well. In all areas, it was a time when old barriers were being broken down, when people were finding new ways of expressing themselves. It was the birth of modernism.

And, at first glance, the developments in physics fit right into story. There was a keen sense -- even in the popular press -- that Einstein's theories were a revolution, that they had unmoored us from the absolutes of Newton's world. This was even more pronounced a decade later when quantum mechanics was developed which introduced uncertainty into physics and told us that on the deepest level reality is much stranger than anything we'd ever imagined before.

On the one hand, the developments in physics certainly fit the spirit of the time. But on the other, it's very hard to see how these developments in different fields --- especially in physics --- can really have anything to do with each other. This is because the route that physics takes isn't decided by physicists. We don't get to chose what the laws of physics are. Nature choses that. If we come up with some new avant-garde way of thinking which really impresses out colleagues, it doesn't mean that much. Because, at the end of the day, it's only experiment which decides what is right and what it wrong.

Of course, it's possible that developments in physics influenced the arts. Some of the timing works out: Picasso's breakthrough work was painted in 1907, two years after the theory of special relativity. And great books have been written exploring the connection between cubism, relativity and the fourth dimension of time. But whether this connection is really nothing more than coincidence, or whether there are deeper underlying roots, remains --- at least to me --- unclear.

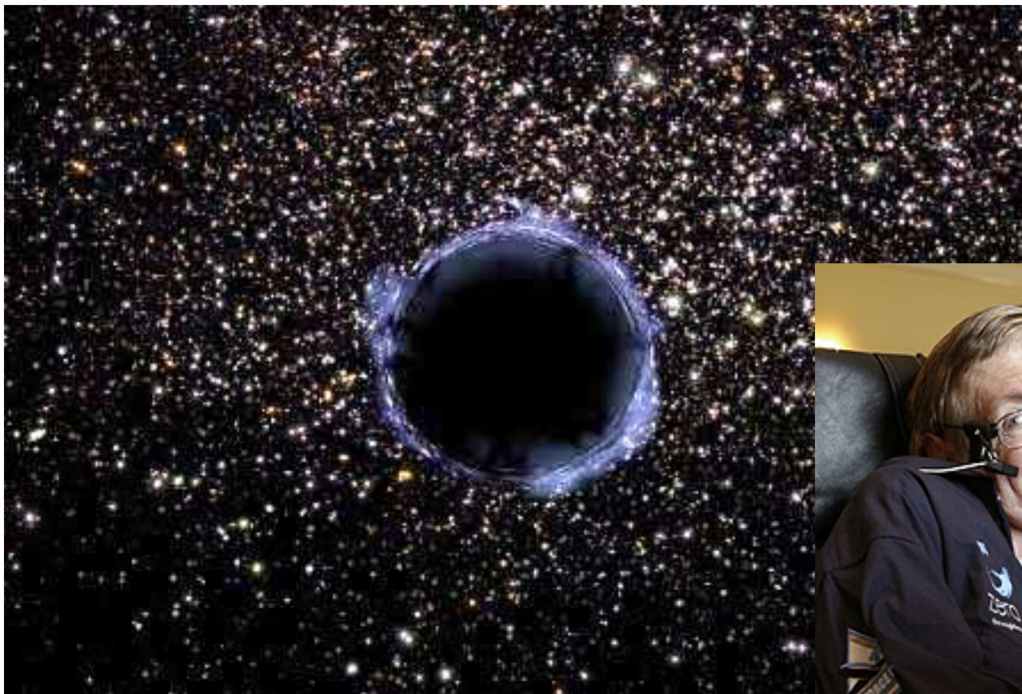
Scientific Legacy: Cosmology

Finally, I want to tell you about the legacy of general relativity in science. How Einstein's theory influences the kind of things that we're doing now.

Cosmology is the study of the Universe as a whole, where it came from, how big is it? how will it end? Grand questions. And this whole field of study is only possible because of the framework of general relativity. Soon after Einstein's theory, we learned something extraordinary, one of the most important facts in science: the Universe hasn't always been the way it is. It is not eternal. There was a time in the past -- a time that's called the Big Bang -- when the Universe was much smaller, there were no stars or planets, instead it was filled with a hot dense fireball, out of which everything we see emerged. This time was 13.7 billion years ago.

It's worth stressing how well we understand this: when I was at university in the 1990s we knew that the Universe was somewhere between 8 billion and 20 billion years old. Now we know for sure: 13.7 billion. We know the decimal point. This has all happened in the past 10 years or so. And the next 10 years are going to see us understanding this beginning much better. And this is all possible because of Einstein.

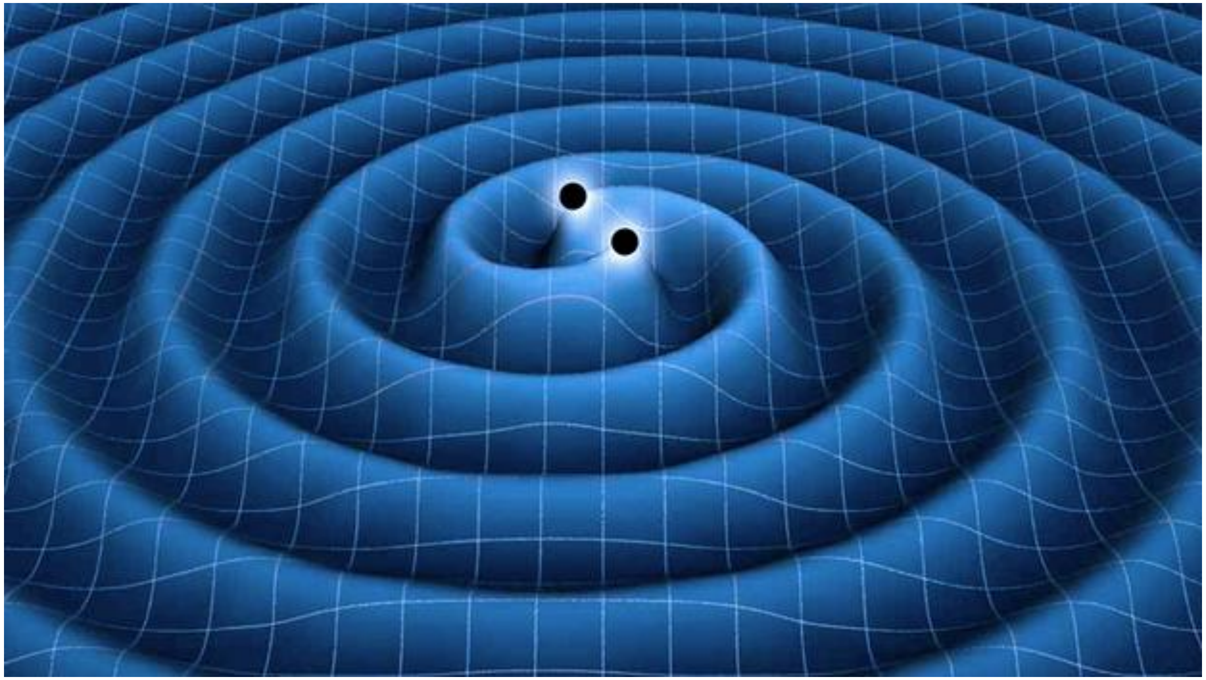
Scientific Legacy: Black Holes



Black holes are perhaps the biggest mystery of Einstein's theory. They are regions of space where the bending gets so great that light itself gets trapped. They exist in our Universe. And they are things that we really don't understand at all.

In some sense, Stephen Hawking’s great contribution to science was to convince us all that none of us understood black holes. He laid down a gauntlet to physicists to try to make sense of black holes; and no one has yet fully succeeded. Black holes remain one of the biggest open problems in theoretical physics.

Gravity Waves: Ripples in Space



Coming soon!

For the final legacy, I want to return to Einstein's original puzzle. Suppose that our Sun did explode. What would happen. Well, the explosion would send out ripples in space, concentric rings that would spread out as if you dropped a stone in a pond. And it's those ripples, which move at the speed of light, which would tell the Earth that something had happened with gravity.

Thankfully our Sun hasn't exploded, but there are plenty of other violent events in the Universe. Stars exploding, black holes colliding. Which means that space is full of these ripples, moving in all directions. We call them "gravity waves". They've never been observed but they're the last great prediction of Einstein's theory.

Right now, there are incredible experiments up and running looking for these ripples in the spacetime continuum. It seems very likely that, within the next 5 years or so, we're going to see these things and finally confirm all of Einstein's predictions.

Usually when you give science talks, you're supposed to stress the technological advances that come out of the science, the benefits to the economy.

But I didn't want to do that here. There are technological advances. Many satellites that fly rely on Einstein's theory of general relativity. The GPS system in your phone or in your satnav relies on general relativity. And I like as much as anyone that I can click on my phone and find the nearest restaurant. That's brilliant.

But that's not what this is about. It's not why Einstein's theory is one of the great contributions to human culture. It would be like saying that classical music is important because you can use it in adverts to sell Renault Clios.

So I'd like to leave you with a quote of Einstein himself who, as usual, understood better than most what was going on.

“I was originally supposed to have become an engineer, but the thought of having to expend my creative energy on things that make practical everyday life even more refined, with bleak capital gain as the goal was unbearable to me.

Thinking for its own sake. Like music!"

Albert Einstein

Thank you for your attention

THE REST IS NOISE