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WHAT HAS EINSTEIN EVER DONE FOR YOU?

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Albert Einstein's mind-boggling ideas revolutionized our view of the universe. From relativity to curved spacetime, from the Big Bang to black holes and gravitational waves, nothing could be further from our everyday experience than such esoteric concepts, right? Wrong! This lecture will offer a surprising exploration of the wide-ranging consequences of Einstein's ideas, and how they shape our everyday life.

The Birth of a Genius

Albert Einstein has defined in an almost archetypical way what it means to be a physics genius: dishevelled hair, head in the clouds, perennially lost in thoughts incomprehensible to mere mortals. His fame was forged overnight. In 1919, the great English astronomer Arthur Eddington led one of two expeditions to measure the apparent position of stars around the rim of the Sun during a solar eclipse. Eddington's mission was to check Einstein's prediction, made using his novel theory of General Relativity, about the deflection of light created by the curvature of spacetime around the Sun. When reporting the result, which fully vindicated Einstein's model, the New York Times on Nov 10th, 1919 led with "Einstein Theory Triumphs […] A book for 12 wise men. No more in All the World Could Comprehend it, Said Einstein when His Daring Publishers Accepted it".

Einstein's ideas have, ever since then, come to be associated with exotic, abstruse, fiendishly difficult and ultimately very far-away realities: the curvature of spacetime, the properties of black holes, the slowing down of time when traveling to speeds close to that of light, the expansion of the Universe, gravitational waves, the Big Bang. All of these concepts appear to have one thing in common: they pertain to extreme domains of physics, far-removed from everyday life and apparently irrelevant to most of us.

But a closer look reveals that Einstein's ideas reach deep into our everyday life, in many more ways than one would imagine.

Einstein vs Newton

In order to appreciate the importance of Einstein's revolutionary impact on physics, we must first take a step back and consider another great physicist – Sir Isaac Newton. Newton formulated in 1687 the Law of Universal Gravitation, inspired by the famous apple falling from the tree in his garden at Woolsthorpe Manor, in Lincolnshire, in the Summer of 1666 (the story appears to be genuine, as Newton himself relayed different versions of it to several of his friends, although it "got better with the telling", as Keith Moore, head of archives at the Royal Society, put it).

According to Newton's theory, gravity is a force proportional to the mass of the object and it diminishes according to the square of the distance from it. The same force that keeps the Moon in a circular orbit around the Earth is also responsible for attracting the apple towards the ground and making it fall.

Together with his Three Laws of Motion, Newton's Theory of Gravitation describe a universe where a meter is a meter anywhere in the cosmos, and a second lasts a second at any place and time: a clockwork universe.

By contrast, Einstein's theory of General Relativity upends the notion of gravity: according to Einstein, gravity is not a force, but rather a manifestation of the geometry of spacetime. The presence of mass changes the shape of spacetime, which bends and is deformed like a rubber sheet when a cannonball is placed in its middle. In turn, the shape of spacetime dictates how mass – and, as we shall see below, light -- move through the cosmos.

When Einstein began thinking about gravity, he formulated a simple yet powerful principle: that the acceleration due to gravity should be experimentally indistinguishable from the acceleration due to any other force. This is called "the equivalence principle". The equivalence principle implies that if I am in a sealed box with no view of my surrounding and I observe an apple fall with uniformly accelerated motion, I have no way of determining whether the apple falls because the box is sitting still on the surface of the Earth (and the apple's acceleration is due to gravity) or because the box itself is accelerating upwards in empty space.

A profound consequence of the equivalence principle is that the trajectory of light must be bent in the presence of mass, too, for otherwise shooting a light beam across the box would give me a way of distinguishing between the two situations. Gravity bends light. Therefore, Einstein concluded, light must deviate from a straight line when it passes near a massive object like the Sun. More accurately, a bent trajectory is the shortest path in a spacetime deformed by the mass of the Sun. This prediction of General Relativity differs from what one would expect under Newtonian gravity: the bending angle between the "straight line" trajectory and the bent one is twice as large in General Relativity as it is in Newtonian gravity (where it can be computed with a fudge but without really explaining why light, which is massless, ought to feel gravity).

This is precisely what was observationally verified by the 1919 Eddington solar eclipse expedition. Today, the same principle is applied on cosmological scales to investigate dark matter, and to use this "gravitational lens" effect to see galaxies that would otherwise be too far away for us to detect.

Einstein's Exotica

Almost immediately after it was proposed in 1915 by Einstein, General Relativity was used by many other physicist and mathematicians, eager to work out its implications for our understanding of the cosmos.

The German astronomer Karl Schwarzschild realized already in 1916 that spacetime would be deformed to the extreme by concentrating a sufficiently large mass in a sufficiently small volume: a singularity ensues, which we can imagine as a puncture in the fabric of spacetime. A black hole is precisely that: a concentration of mass so extreme that not even light can escape the "funnel" of spacetime around it. An amazing picture of the silhouette of a black hole in the M87 galaxy, 53 million light year away, was obtained for the first time in 2019, and made headlines around the world (Figure 1). The picture shows the accretion ring, i.e., the hot gas than envelops the black hole's event horizon, the region out of which light cannot escape.

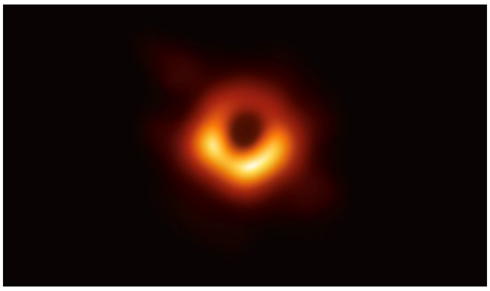

Figure 1: The event horizon (black disc) and accretion disk (luminous ring) of the black hole in the M87 galaxy. Credit: EHT collaboration.

In a paper he published in 1975, Steven Hawking proposed that black holes cannot be wholly black: they must "evaporate" over time, by emitting energy that is now called "Hawking radiation". We shall see later that the quest to detect such a faint signal led to the invention of Wi-Fi.

The deformable nature of Einstein's spacetime also means that waves can travel through it. These gravitational waves are of a different nature than other waves we might be familiar with (like sound waves in air, or sea waves, or electromagnetic waves such as light). Already in 1916, Einstein predicted the existence of gravitational waves. Gravitational waves are produced when two massive objects like two black holes or two neutron stars orbit each other: the energy that is emitted in the form of gravitational waves, which travel out at the speed of light, is lost from the binary system. This means that the orbits shrink, until the two black holes or neutron stars merge in a fatal embrace. As they travel through space, gravitational waves stretch space in one direction (say vertically on the face of a clock) and compress it in another (horizontally on the face of a clock). This is a smoking gun signature that can be picked up by sensitive detectors by using laser beams to measure the changes in length in the arms of an L-shaped system.

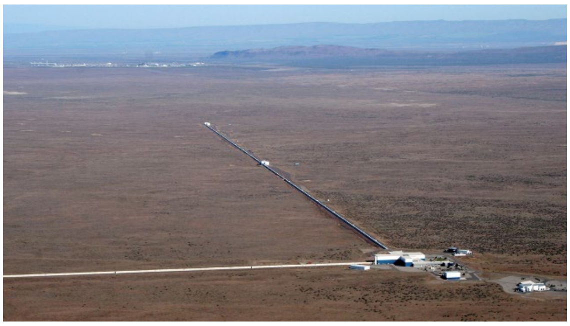

Figure 2: The Laser-Interferometer Gravitational-wave Observatory at the Hanford site, Washington. Credit: LIGO Collaboration.

This gravitational wave signal is extraordinarily small: the change in length between the two arms, each 4 km long, is less that 1/10,000 of the width of a proton. Exceptional care must be taken to shield the detector from every interference, including the gravitational pull of passing clouds (!). Nevertheless, this amazing feat of engineering and physics has been achieved, for the first time, in Sept 2015, and the leading physicists behind the discovery were awarded the Nobel Prize for Physics in 2017. Now, gravitational wave astronomy is rapidly becoming commonplace, with several blackholes merger events and two neutron stars merger detected to date. Soon, these measurements will allow astronomers to measure the expansion rate of the universe with great precision.

Einstein used his new theory of General Relativity to describe the universe as a whole, and in 1917 came up with the idea of a static universe, one that wasn't changing with time, in according with his beliefs. In order to achieve that, he had to massage the equations of General Relativity by introducing an additional term, counteracting gravity. But in 1922, the Russian physicist and mathematician Alexander Friedmann showed that Einstein's theory allowed for solutions that described an *expanding* universe – which was observationally confirmed in 1929 by Edwin Hubble. Today, a large amount of cosmological data (from the leftover radiation from the Big Bang to the distribution of galaxies in the cosmos) can only be interpreted and understood thanks to the tools offered by General Relativity.

Einstein's ideas have been revolutionary in astronomy, astrophysics and cosmology. One might therefore conclude that his work, while incredibly powerful in investigating the universe, is utterly irrelevant for our everyday life.

Nothing could be farther from the truth.

Einstein's Gifts

In fact, Einstein's ideas shape our life every day. His work eventually made possible the GPS, nuclear power, wireless technology and digital cameras. In the near future, we might reap the benefits of quantum computers, which also originate from his ideas.

Let's return to the equivalence principle that was discussed earlier and put ourselves back in the sealed box. Imagine shooting a light beam from the floor of the box to a detector in the ceiling, and suppose the sealed box is being accelerated upwards in deep space. By the time the light has reached the detector, the ceiling has accelerated away and hence the detector will see a slightly longer wavelength. The light has been "redshifted" and has thus lost some of its energy. But by the equivalence principle, the same must be true if the box is actually sitting still in a gravitational field with the same acceleration. Therefore, light is gravitationally redshifted (i.e., it loses energy and its frequency decreases) as it moves away from a massive body.

Consider now the number of light waves emitted by the light source at the bottom of the box in a certain time interval, say 1 second, as measured by a clock placed next to the light source. By the definition of frequency (i.e., cycles per unit time), the number of crests of light waves is given by the product of the time interval and the light frequency. When we now measure the same number of crests with the detector in the ceiling, we know that the light frequency there is larger due to it being redshifted. This means that the time interval, as measured by a clock in the ceiling, must be smaller: time flows more quickly near the ceiling (further away from the mass of the Earth) than at the bottom. This gravitational time dilation effect has been verified experimentally in 1960. It means that a second measured by a clock at sea level corresponds to 1.00000000000008 seconds on top of the Everest. So, if you want your holidays to last for longer, go to the seaside!

We can also compare the flow of time in the proximity of bodies of different mass: time slows down near more massive bodies. For example, if we took two identical atomic clocks and placed the first one on the surface of the Earth and the second near the surface of the Sun (provided it could withstand the temperature!), after a year as measured by the Earth clock, the clock on the Sun would appear to be slower by 1 and a half minutes. If we placed the second clock on the surface of a neutron star, where the mass concentration and hence the time dilation effect are much stronger, it would appear to have slowed down by 1 hour and a half!

These effects matter in a very practical way: the Global Positioning System (GPS) we all rely on for navigation and many other uses, works by triangulating radio signals from 4 satellites, orbiting the earth at an altitude of approximately 20,000 km, and circling the Earth twice a day. The curvature of spacetime induced by the Earth's mass at the surface at the Earth and at the location of the satellites is sufficiently different that the GPS system inside your phone needs to account for the time difference due to General Relativity, on top of another (smaller) effect due to special relativity. When combined, these two effects mean that the GPS in your phone would be off by 10 km after a single day, unless the general and special relativistic corrections are accounted for. Without Einstein, we wouldn't be able to use geolocation and navigate e.g. by Google Maps, something that has become an indispensable tool today.

Nuclear power generation is at heart made possible by Einstein's famous energy-mass equivalence relation: $E= mc^2$. Nuclear reactors exploit the fact that a tiny amount of mass of the nuclear fuel is converted via fission into an enormous amount of heat, which then produces electricity via turbines. The same idea can also lead to the unleashing of the immensely destructive power of nuclear weapons, unfortunately – something the Einstein fought against strenuously in the latter part of his life. If we can achieve fusion in a controlled manner, however, we would access a practically inexhaustible source of clean energy for humankind.

Wireless internet in the form of Wi-Fi is a daily experience for billions of people that might not have existed had it not been for black holes – another consequence of Einstein's General Relativity theory, as we saw. In the early Nineties, John O'Sullivan, an Australian electrical engineer, was working on an algorithm to clean the radio signals coming from the cosmos, in a quest to isolate the faint whisper expected from evaporating black holes, as predicted by Hawking. In so doing, he realized that his method of boosting faint signals could be used to improve data connections – the core idea behind modern Wi-Fi was born.

Digital cameras are the final outcome of a daisy chain of scientific discoveries and technological advances that stretch back to Einstein himself. At the turn of the 19th century, physicists were puzzled by an unexplainable mystery, called "the photoelectric effect". The observation was that electricity would flow from a metal when it was irradiated with light – the interpretation being that electrons in the metal's atoms were freed by the energy supplied by the light, and thus gave an electric current. The puzzle was that only light of a certain colour would lead to an electric current flowing. If one used light with a longer wavelength (i.e. redder light), no current would ever flow, no matter the intensity of the light nor the time of irradiation. This did not make any sense in the classical picture of light as a wave.

Einstein however took this as the springboard for the quantum revolution: he realized that the mystery could be solved if light was made of discrete "packets" of energy, the photons, each of which could only carry a certain amount of energy, related to the colour of the light (and thus its wavelength). Individual red-light photons, he said, carry insufficient energy to knock electrons off their atomic orbits. Light of shorter wavelength, by contrast, packs more energy in each photon, sufficient to free the electrons and generate the observed current. This was a prime example of the wave-particle duality that would in time pervade all of quantum mechanics. For his explanation of the photoelectric effect, Einstein was awarded the Nobel Prize for Physics in 1921 – an accolade he hadn't won (controversially) for his equally revolutionary invention of special and general relativity.

What Will Einstein Do for You?

The next big revolution in computing, namely quantum computers, might be realized in the near future – and Einstein's fingerprints will be all over it. While conventional computers work with binary digits, which can only take on the value of either 0 or 1, quantum computers exploit the ability of quantum bits (or "q-bits") to be in a quantum superposition of values – i.e., of being *simultaneously* in both the 0 and the 1 state, and anything in between. If it can be harnessed, this characteristic makes quantum computers immeasurably faster than traditional computers at certain kinds of tasks. There are presently somewhat controversial claims that working quantum computers have achieved what is called "quantum supremacy" – the ability to surpass the speed of traditional computers by orders of magnitude.

Einstein, with Podolski and Rosen, was the first to highlight in 1935 the key property of quantum systems that makes them suitable for modern quantum computing, namely "quantum entanglement". Einstein was sceptical about quantum mechanics: in a letter to Born, he wrote in 1926: "Quantum theory yields much, but it hardly brings us close to the Old One's secrets. I, in any case, am convinced He does not play dice with the universe." In the hope of debunking the idea of quantum entanglement, which he called "spooky action at a distance" in 1947, he proposed a thought experiment that in his view showed that quantum mechanics was incomplete. He was however wrong, and quantum entanglement was experimentally proven in the 1960s, in efforts partially inspired by Einstein's thought experiment.

Even in his mistakes, Einstein remains an unparalleled genius.

So next time you ask yourself "What has Einstein ever done for me?", remember to thank old Albert for so many of the marvels of modern science and technology!

Further Reading

- John D. Barrow, "The Book of Universes: Exploring the Limits of the Cosmos", W.W. Norton & Company (2013).
- Chris Impey, "Einstein's Monsters: The Life and Times of Black Holes", W.W. Norton & Company (2018)
- STFC Impact Report (2017), Science and Technologies Facilities Council (UK). Available from: https://stfc.ukri.org/files/stfc-impact-report-2017/ (accessed Jan 30th 2019).
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- Brian Clegg, Gravitational Waves: How Einstein's spacetime ripples reveal the secrets of the universe, Icon Books (2018).