

Miraculous Year (1905)

Poincaré & Einstein

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In his 1902 book "La Science et l'Hypothèse", the mathematical physicist Henri Poincaré identified three fundamental yet unresolved problems [in physics].

One problem concerned the mysterious way ultraviolet light ejects electrons from the surface of a metal;

the second problem was the zig-zagging perpetual motion of pollen particles suspended in a liquid;

the third problem was the failure of experiments to detect Earth's motion through the aether.

In 1904, Einstein read Poincaré's book. He had also been thinking about these problems, independently of Poincaré. For Einstein, they were clearly part of God's thoughts. One year later, in 1905, he solved all three.

Adapted from "Five papers that shook the world"
by Matthew Chalmers
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Most physicists would be happy to make one discovery that is important enough to be taught to future generations of physics students. Only a very small number manage this in their lifetime, and even fewer make two appearances in the textbooks.

But Einstein was different. In little more than eight months in 1905 he completed five papers that would change the world for ever. Spanning three quite distinct topics - relativity, the photoelectric effect and Brownian motion - Einstein overturned our view of space and time, showed that it is insufficient to describe light purely as a wave, and laid the foundations for the discovery of atoms.

Genius at work

Perhaps even more remarkably, Einstein's 1905 papers were based neither on hard experimental evidence nor sophisticated mathematics. Instead, he presented elegant arguments and conclusions based on physical intuition.

"Einstein's work stands out not because it was difficult but because nobody at that time had been thinking the way he

did," says Gerard 't Hooft of the University of Utrecht, who shared the 1999 Nobel Prize for Physics for his work in quantum theory.

"Dirac, Fermi, Feynman and others also made multiple contributions to physics, but Einstein made the world realize, for the first time, that pure thought can change our understanding of nature."

And just in case the enormity of Einstein's achievement is in any doubt, we have to remember that he did all of this in his "spare time".

Statistical revelations

In 1905 Einstein was married with a one-year-old son and working as a patent examiner in Bern in Switzerland. His passion was physics, but he had been unable to find an academic position after graduating from the ETH in Zurich in 1900.

Nevertheless, he had managed to publish five papers in the leading German journal *Annalen der Physik* between 1900 and 1904, and had also submitted an unsolicited thesis on molecular forces to the University of Zurich, which was rejected.

Most of these early papers were concerned with the reality of atoms and molecules, something that was far from certain

at the time. But on 17 March in 1905 - three days after his 26th birthday - Einstein submitted a paper titled "A heuristic point of view concerning the production and transformation of light" to Annalen der Physik.

Einstein suggested that, from a thermodynamic perspective, light can be described as if it consists of independent quanta of energy (Ann. Phys., Lpz 17 132-148).

This hypothesis, which had been tentatively proposed by Max Planck a few years earlier, directly challenged the deeply ingrained wave picture of light. However, Einstein was able to use the idea to explain certain puzzles about the way that light or other electromagnetic radiation ejected electrons from a metal via the photoelectric effect.

Maxwell's electrodynamics could not, for example, explain why the energy of the ejected photoelectrons depended only on the frequency of the incident light and not on the intensity. However, this phenomenon was easy to understand if light of a certain frequency actually consisted of discrete packets or photons all with the same energy.

Einstein would go on to receive the 1921 Nobel Prize for Physics for this work, although the official citation stated that the prize was also awarded "for his services to theoretical physics".

"The arguments Einstein used in the photoelectric and

subsequent radiation theory are staggering in their boldness and beauty," says Frank Wilczek, a theorist at the Massachusetts Institute of Technology who shared the 2004 Nobel Prize for Physics.

"He put forward revolutionary ideas that both inspired decisive experimental work and helped launch quantum theory." Although not fully appreciated at the time, Einstein's work on the quantum nature of light was the first step towards establishing the wave-particle duality of quantum particles.

On 30 April, one month before his paper on the photoelectric effect appeared in print, Einstein completed his second 1905 paper, in which he showed how to calculate Avogadro's number and the size of molecules by studying their motion in a solution.

This article was accepted as a doctoral thesis by the University of Zurich in July, and published in a slightly altered form in *Annalen der Physik* in January 1906.

Despite often being obscured by the fame of his papers on special relativity and the photoelectric effect, Einstein's thesis on molecular dimensions became one of his most quoted works.

Indeed, it was his preoccupation with statistical mechanics that formed the basis of several of his breakthroughs,

including the idea that light was quantized.

After finishing a doctoral thesis, most physicists would be either celebrating or sleeping. But just 11 days later Einstein sent another paper to *Annalen der Physik*, this time on the subject of Brownian motion.

In this paper, "On the movement of small particles suspended in stationary liquids required by the molecular-kinetic theory of heat", Einstein combined kinetic theory and classical hydrodynamics to derive an equation that showed that the displacement of Brownian particles varies as the square root of time (*Ann. Phys.*, Lpz 17 549-560).

This was confirmed experimentally by Jean Perrin three years later, proving once and for all that atoms do exist. In fact, Einstein extended his theory of Brownian motion in an additional paper that he sent to the journal on 19 December, although this was not published until February 1906.

A special discovery

Shortly after finishing his paper on Brownian motion Einstein had an idea about synchronizing clocks that were spatially separated.

Adapted from "The Mechanical Universe"

Episode 43: Velocity and Time

In the 1800s Michael Faraday discovered, or I should say formalized, electromagnetic induction. Given a coil of wire and a bar magnet...

$$\mathbf{F} = q\mathbf{E} + q\mathbf{v} \times \mathbf{B}$$

Holding the coil stationary and moving the bar magnet produced an electric current in the coil. Similarly holding the bar magnet stationary and moving the coil also produced an electric current in the coil.

But in the language of electrodynamics of the day the two cases were distinct independent phenomena that had completely different explanations.

When Albert Einstein saw that, he said "Look guys, you've just got to be kidding--Any yo-yo can see that these are the same thing".

So it was this little experiment that was really the start of relativity, not the Michelson-Morley Experiment--not some exotic experiment to detect the motion of the earth through the aether.

With this simple little phenomenon, that of course everybody knew about, disturbed nobody else, but Albert Einstein.

This led him to write a paper that landed on the desks of Annalen der Physik on 30 June, and would go on to completely overhaul our understanding of space and time. Some 30 pages long and containing no references, his fourth 1905 paper was titled "On the electrodynamics of moving bodies" (Ann. Phys., Lpz 17 891-921).

In the 200 or so years before 1905, physics had been built on Newton's laws of motion, which were known to hold equally well in stationary reference frames and in frames moving at a constant velocity in a straight line. Provided the correct "Galilean" rules were applied, one could therefore transform the laws of physics so that they did not depend on the frame of reference.

However, the theory of electrodynamics developed by Maxwell in the late 19th century posed a fundamental problem to this "principle of relativity" because it suggested that electromagnetic waves always travel at the same speed.

Either electrodynamics was wrong or there had to be some kind of stationary "ether" through which the waves could propagate.

I just want to read to you the first two paragraphs of Einsteins 4th paper...

ON THE ELECTRODYNAMICS OF MOVING BODIES

By A. Einstein

June 30, 1905

It is known that Maxwell's electrodynamics--as usually understood at the present time--when applied to moving bodies, leads to asymmetries which do not appear to be inherent in the phenomena.

Take, for example, the reciprocal electrodynamic action of a magnet and a conductor. The observable phenomenon here depends only on the relative motion of the conductor and the magnet, whereas the customary view draws a sharp distinction between the two cases in which either the one or the other of these bodies is in motion. For if the magnet is in motion and the conductor at rest, there arises in the neighbourhood of the magnet an electric field with a certain definite energy, producing a current at the places where parts of the conductor are situated.

But if the magnet is stationary and the conductor in motion, no electric field arises in the neighbourhood of the magnet. In the conductor, however, we find an electromotive force, to which in itself there is no corresponding energy, but which gives rise--assuming equality of relative motion in

the two cases discussed--to electric currents of the same path and intensity as those produced by the electric forces in the former case.

Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relatively to the "light medium," suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest.

They suggest rather that, as has already been shown to (1) the first order of small quantities, the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good. We will raise this conjecture (the purport of which will hereafter be called the ``Principle of Relativity'') to the status of a postulate,

and also introduce another postulate, which is only (2) apparently irreconcilable with the former, namely, that light is always propagated in empty space with a definite velocity c which is independent of the state of motion of the emitting body.

These two postulates suffice for the attainment of a simple and consistent theory of the electrodynamics of moving bodies based on Maxwell's theory for stationary bodies.

The introduction of a "luminiferous ether" will prove to be

superfluous inasmuch as the view here to be developed will not require an "absolutely stationary space" provided with special properties, nor assign a velocity-vector to a point of the empty space in which electromagnetic processes take place.

And, of course the paper goes on to develop the ideas and make his case...

True to style, Einstein swept away the concept of the ether (which, in any case, had not been detected experimentally) in one audacious step. He postulated that no matter how fast you are moving, light will always appear to travel at the same velocity: the speed of light is a fundamental constant of nature that cannot be exceeded.

Combined with the requirement that the laws of physics are the identical in all "inertial" (i.e. non-accelerating) frames, Einstein built a completely new theory of motion that revealed Newtonian mechanics to be an approximation that only holds at low, everyday speeds.

The theory later became known as the special theory of relativity - special because it applies only to non-accelerating frames - and led to the realization that

space and time are intimately linked to one another.

In order that the two postulates of special relativity are respected, strange things have to happen to space and time, which, unbeknown to Einstein, had been predicted by Lorentz and others the previous year.

For instance, the length of an object becomes shorter when it travels at a constant velocity, and a moving clock runs slower than a stationary clock.

Effects like these have been verified in countless experiments over the last 100 years, but in 1905 the most famous prediction of Einstein's theory was still to come.

After a short family holiday in Serbia, Einstein submitted his fifth and final paper of 1905 on 27 September. Just three pages long and titled "Does the inertia of a body depend on its energy content?", this paper presented an "afterthought" on the consequences of special relativity, which culminated in a simple equation that is now known as $E = mc^2$ (Ann. Phys., Lpz 18 639-641).

This equation, which was to become the most famous in all of science, was the icing on the cake.

"The special theory of relativity, culminating in the prediction that mass and energy can be converted into one another, is one of the greatest achievements in physics - or

anything else for that matter," says Wilczek.

"Einstein's work on Brownian motion would have merited a sound Nobel prize, the photoelectric effect a strong Nobel prize, but special relativity and $E = mc^2$ were worth a super-strong Nobel prize."

However, while not doubting the scale of Einstein's achievements, many physicists also think that his 1905 discoveries would have eventually been made by others.

"If Einstein had not lived, people would have stumbled on for a number of years, maybe a decade or so, before getting a clear conception of special relativity," says Ed Witten of the Institute for Advanced Study in Princeton.

't Hooft agrees. "The more natural course of events would have been that Einstein's 1905 discoveries were made by different people, not by one and the same person," he says. However, most think that it would have taken much longer - perhaps a few decades - for Einstein's general theory of relativity to emerge.

Indeed, Wilczek points out that one consequence of general relativity being so far ahead of its time was that the subject languished for many years afterwards.

The aftermath

By the end of 1905 Einstein was starting to make a name for himself in the physics community, with Planck and Philipp Lenard - who won the Nobel prize that year - among his most famous supporters. Indeed, Planck was a member of the editorial board of *Annalen der Physik* at the time.

Einstein was finally given the title of Herr Doktor from the University of Zurich in January 1906, but he remained at the patent office for a further two and a half years before taking up his first academic position at Zurich.

By this time his statistical interpretation of Brownian motion and his bold postulates of special relativity were becoming part of the fabric of physics, although it would take several more years for his paper on light quanta to gain wide acceptance.

1905 was undoubtedly a great year for physics, and for Einstein. "You have to go back to quasi-mythical figures like Galileo or especially Newton to find good analogues," says Wilczek.

"The closest in modern times might be Dirac, who, if magnetic monopoles had been discovered, would have given Einstein some real competition!" But we should not forget that 1905 was just the beginning of Einstein's legacy. His crowning achievement - the general theory of relativity - was still to come.

