Five papers that shook the world

In 1905 an anonymous patent clerk in Bern rewrote the laws of physics in his spare time. **Matthew Chalmers** describes Einstein's miraculous year

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.

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.

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Genius at work – Einstein was just 26 when he made three ground-breaking contributions to physics in a single year. Here he is pictured at the Swiss patent office in early 1906.

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 (see "Einstein's random walk" on page 19). 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.

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A special discovery

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

Elsewhere in 1905

Einstein's *annus mirabilis* tends to overshadow other scientific developments that took place in 1905. So what else was going on in the year that cellophane was invented, the neon sign made its debut, and people were getting to grips with tea bags for the first time? In terms of the number of citations in physics and physical-chemistry journals since 1945, three of Einstein's 1905 papers feature in the top five, according to Werner Marx and Manuel Cardona of the Max Planck Institute for Solid State Research in Stuttgart. Indeed, his papers on Brownian motion and special relativity take first and second place, respectively, with 1467 and 642 citations (his papers on the photoelectric effect and $E=mc^2$ are fifth and 11th). The fourth most-cited paper of 1905 was by Paul Langevin, who derived a fundamental formula in kinetic theory – clearly a popular subject at the time – while Lawrence Bragg published a paper about the energy loss of alpha particles in different media, which became the sixth most-cited paper of the year.

Hendrik Antoon Lorentz, who was influential in the development of special relativity, was elected as a fellow of the Royal Society in 1905 and published several papers, including one on the motion of electrons in metallic bodies. Nuclear physics was also a subject of intense interest at the time, with Ernest Rutherford and Frederick Soddy publishing their theory of nuclear transmutation and Bertram Boltwood demonstrating that lead is the final product of uranium decay. Further afield, Victor Goldschmidt introduced a method to reduce metallic oxides to metals, while Haldane and Priestley demonstrated the role of carbon dioxide in the regulation of breathing.

Outside the world of science, an unsuccessful revolution was beginning in Russia, Antonio Gaudi began two of his famous buildings in Barcelona, and H G Wells had written *Kipps*. Meanwhile, Jean-Paul Sartre and Henry Fonda were born, as was the Nobel-prize-winning physicist Emilio Segrè, who 40 years later would witness the application of $E=mc^2$ with the detonation of the first atomic bomb. **MC**