A century after Einstein's miracle year, most people still do not understand exactly what it was he did. Here, we attempt to elucidate

IN THE span of 18 months, Isaac Newton invented calculus, constructed a theory of optics, explained how gravity works and discovered his laws of motion. As a result, 1665 and the early months of 1666 are termed his *annus mirabilis*. It was a sustained sprint of intellectual achievement that no one thought could ever be equalled. But in a span of a few years just before 1900, it all began to unravel. One phenomenon after another was discovered which could not be explained by the laws of classical physics. The theories of Newton, and of James Clerk Maxwell who followed him in the mid-19th century by crafting a more comprehensive account of electromagnetism, were in trouble.

Then, in 1905, a young patent clerk named Albert Einstein found the way forward. In five remarkable papers, he showed that atoms are real (it was still controversial at the time), presented his special theory of relativity, and put quantum theory on its feet. It was a different achievement from Newton's year, but Einstein's *annus mirabilis* was no less remarkable. He did not, like Newton, have to invent entirely new forms of mathematics. However, he had to revise notions of space and time fundamentally. And unlike Newton, who did not publish his results for nearly 20 years, so obsessed was he with secrecy and working out the details, Einstein released his papers one after another, as a fusillade of ideas.

For Einstein, it was just a beginning—he would go on to create the general theory of relativity and to pioneer quantum mechanics. While Newton came up with one system for explaining the world, Einstein thus came up with two. Unfortunately, his discoveries—relativity and quantum theory—contradict one another. Both cannot be true everywhere, although both are remarkably accurate in their respective domains of the very large and the very small. Einstein would spend the last years of his life attempting to reconcile the two theories, and failing. But then, no one else has succeeded in fixing the problems either, and Einstein was perhaps the one who saw them most clearly.

A noble prize

When Einstein was awarded a Nobel prize, in 1921, it was for the first of his papers of 1905, which proved the existence of photons—particles of light. Up until that paper, completed on March 17th and published in *Annalen der Physik* (as were the other 1905 papers), light had been supposed to be a wave, since this explains the interference patterns created when it passes through a grating. Einstein, however, began from a different premise, by considering the so-called "black-body experiment".

A black body is a notional heated box that emits electromagnetic radiation (light, and its cousins such as radio and X-rays) at all frequencies. One of the main problems of physics at the turn of the century was that black-body radiation was predicted to increase indefinitely at higher frequencies, which was physically impossible. Five years earlier, Max Planck, a respected elder statesman of German physics, had supposed that a black body could emit radiation only at discrete frequencies. The gaps between these frequencies are the quantum jumps from which quantum theory ultimately derives its name. Quantising radiation in this way gets round the problem of indefinitely increasing frequencies.

Planck, however, stopped short of making the deduction that quantising light means that it is made of particles rather than waves. Einstein, by contrast, concluded just that. Furthermore, he went on to show how this assumption explained the photoelectric effect, another physical mystery of the time.

The photoelectric effect occurs when light shines on to an electrical conductor. The light knocks electrons out of their orbits and causes a current to flow. The paradox was that shining a brighter beam at the conductor did not increase the voltage, although the current increased. The light, in other words, was producing more electrons, but not more energetic electrons. Turn up the frequency of the light beam, however, and the voltage goes up. Einstein showed that this is explained if light is composed of particles (which only later came to be called photons) whose energy is proportional to their frequency.

Although physics students today are often taught that it was a quirk of the Nobel committee to give the prize to Einstein for his quantum work rather than relativity, the truth is that everyone at the time, including Einstein, believed it to be the more surprising result. When, late in 1905, he sent a friend some reprints of his papers, he said, "I am sending you some papers which may be of interest. Only one of them is revolutionary." He was referring to the photoelectric paper, rather than anything on relativity. As he later wrote, "It was as if the ground had been pulled out from under one's feet, with no firm foundation to be seen anywhere, upon which one could have built." Indeed, the idea that light is made of particles was not truly accepted until 1923, when it was found that electrons could hit light and cause it to gain energy, as well as the reverse.

Local knowledge

Though Einstein's quantum hypothesis eventually became accepted, it had consequences that not even he had foreseen. Up until the late 1920s, quantum theory evolved in an *ad hoc* fashion. It fell to a younger generation of physicists, in a burst in the late 1920s and early 1930s, to codify it into a universal system now known as quantum mechanics. This shows that light is actually neither just a particle nor just a wave, but rather both simultaneously. Similarly, objects traditionally thought of as particles, such as electrons, are also, simultaneously, waves.

Two consequences followed. The first was that chance plays a fundamental role in the interactions of elementary particles, and therefore in the way the world works. Physics, up to that point in history, had been "deterministic". Consequence followed cause with no room for uncertainty. But uncertainty is at the core of quantum mechanics. It is there in the form of Werner Heisenberg's famous "uncertainty principle" that it is impossible to measure both the speed and the location of an object with precision. And it is there in the form of Erwin Schrödinger's equally famous cat, which is simultaneously dead and alive because its fate depends on the quantum properties of an object whose state is indeterminate (rather than merely unknown) until it is measured.

The second consequence is that the world is "non-local". That is to say, quantum interactions occur instantaneously over arbitrarily long distances. What is more, there is no mechanism in quantum mechanics which explains how particles "communicate" to match up their quantum properties in this way. For example, if one particle is spinning in one direction, its partner must spin in the opposite. However, the first particle does not have a definite direction until it is measured (Schrödinger's cat again), so the second particle cannot "know" how to point until a measurement is performed on the first particle, by which time the second particle may be millions of kilometres away. Einstein termed this "spooky action-at-a-distance".

Einstein was profoundly uncomfortable with both uncertainty and non-locality. From that time until the end of his life in 1955 (making 2005 also the 50th anniversary of his death) he worked to eliminate them from physics. But despite the fame of Einstein's statement that "God does not play dice", he did not believe that quantum mechanics was fundamentally incorrect. Indeed, he was the first to propose Schrödinger and Heisenberg—whose reputations were not established at the time—for Nobel prizes. Rather, he believed it was incomplete.

The best analogy here is to temperature. Temperature does not really exist. When something is said to be hot or cold, what is actually being described is the average speed of the molecules of which that something is made. If the molecules are moving quickly, it is hot, and if slowly, then cold. Temperature is merely a succinct encapsulation of this average. Similarly, Einstein believed that quantum mechanics was describing some sort of statistical average of an underlying phenomenon that was deterministic.

In 1935, Einstein, along with two young collaborators, Boris Podolsky and Nathan Rosen, proposed an experiment that would test this idea by probing action-at-a-distance. It was not, however, performed until 1982. And when Alain Aspect and his colleagues at the University of Paris did carry out the measurement, they found that it was Einstein, not quantum theory, which was wrong. Action-at-a-distance, spooky though he thought it, does occur. However, this episode is an excellent illustration of Einstein's contribution to quantum mechanics. By constantly trying to poke holes in the theory, he made it both stronger and clearer.

As clear as daylight

Abraham Pais, a physicist who wrote what is generally regarded as the definitive scientific biography of Einstein, said of his subject that there are two things at which he was "better than anyone before or after him; he knew how to invent invariance principles and how to make use of statistical fluctuations." Invariance principles play a central role in the theory of relativity. Indeed, Einstein had wanted to call relativity the "theory of invariants".

The idea of an invariant, which, largely because of Einstein, became central to physics in the 20th century, is something that stays constant under various transformations. A circle is invariant under rotation, because it looks the same no matter how it spins. A square, on the other hand, is invariant only under rotations of 90°. Rotate it through a right angle, or a multiple of a right angle, and it is indistinguishable from its unrotated self. Rotate it by any other angle, and it will appear different.

Einstein's insight in the special theory was that the speed of light is such an invariant. It is constant, no matter what speed the observer is travelling at. Add to this the condition, first codified by Galileo, that the laws of physics should look the same so long as the observer is in steady motion, and the special theory of relativity follows. But why did Einstein think the speed of light had to be invariant?

He was not a particularly adroit experimenter or mathematician. His power lay in thinking more clearly about the physical consequences of experimental results than any of his contemporaries, or, indeed, than anyone since.

The experiment in question here is called the Michelson-Morley experiment, after Albert Michelson and Edward Morley, who first performed it in 1887. Even though Newton had explained in the 17th century how light behaved, no one knew what it was until the 1860s, when Maxwell showed that it consists of oscillating electric and magnetic fields. This immediately raised the question of what the fields were oscillating in. At that time, no one could conceive of waves which were not vibrations in some medium. The ocean had waves in water, and sound waves travelled through air; it seemed nonsense to imagine that waves could just "be".

For this reason, physicists postulated the existence of the aether—a substance, otherwise undetectable, through which light travelled. But if the Earth was orbiting the sun, and so moving through space, it must be moving through the aether, too. Measure the speed of light in the direction of the Earth's motion, and perpendicular to it, and you would get different answers, the line of reasoning went. This is what Michelson and Morley did. But they found that the two speeds were, in fact, precisely the same.

The experiment was explained by Henrich Lorentz, a Dutch physicist, who came up with the mathematics required for the answer—that there was a contraction in the direction of the Earth's movement, just enough to make the two speeds *seem* the same. Lorentz could not explain how this contraction occurred, though. He speculated that perhaps forces were at work inside molecules, which were, at the time, still hypothetical entities.

What Einstein realised, without adding any new mathematics, but in a profoundly new way nonetheless, was that there was no *seem* about it. Space really was contracting, and time was slowing down. It is just this that Pais was referring to when he said that Einstein was good at picking invariance principles. Everyone had thought that time was invariant. It is not. No one thought the speed of light was. It is.

Ultimately, it was the same skill in discernment that led Einstein to the general theory of relativity. One of the consequences of the speed of light being invariant is that nothing can travel faster than it. Einstein realised this in his first relativity paper of 1905. He did not immediately see another consequence, that the invariant also implied that mass and energy are interchangeable, the rate of exchange being defined by the speed of light and governed by the one equation in physics that most people have heard of: $E=mc^2$, in which "E" represents energy, "m" mass and "c" the speed of light. This equation, whose consequences were played out in Hiroshima and Nagasaki in 1945, occurred to him a few weeks later, and he published it in another paper, which he wrote up in November 1905.

The speed restriction was a problem for Newton's theory of gravity. That is because, according to Newton, gravity travels instantaneously—which, according to Einstein, is an impossibility. This set Einstein to thinking about exactly what mass is.

In 1907, he realised that the feeling a person gets when being pulled to the Earth by gravity is identical in nature to that which he gets while accelerating—being pushed, for instance, against the seatback of an aeroplane when it is taking off. Both of these are related to that person's mass, but classical physics assumed they were different mass-related phenomena. Einstein, however, concluded that because gravity and acceleration seem the same, they are the same.

He dubbed this conjecture the principle of equivalence. However, unlike the case of special relativity, for which Lorentz had worked out the maths beforehand, in this case there was nothing around to which to apply this insight into the way that gravity works. It took Einstein a further nine years, and the help of a mathematician friend named Marcel Grossman, to work out the maths behind the general theory of relativity which, at its heart, is no more than an embodiment of this insight. By incisively and insightfully choosing what had to remain invariant in his theory (based, of course, on the real world), Einstein varied the established conception of what space and time are.

Damn truths and statistics

The second half of Pais's dictum, that Einstein was a great statistician, was shown by work that tends to get lost in the quantum and relativistic brouhaha. Among the things he did in 1905 were to prove that molecules (and thus, by extension, the atoms of which they are composed) actually exist, and to infer their size. This required the use of statistics, because of the large number of molecules involved.

One paper, which also served as his doctoral thesis, inferred the size of molecules from the speed with which sugar dissolves in water. For many years this was his most cited study. A second paper addressed the question of Brownian motion. This is the random motion of small particles, such as dust or pollen, suspended in solution. It had been seen some years before under a microscope, but no one could explain it. Einstein, in a brief and beautifully written paper, explained how the motion was caused by molecules hitting the particles, thus proving that molecules are, indeed, real.

Einstein's use of statistics was also central to the paper about light quantisation and the photoelectric effect. Indeed, he continued applying statistics to quantum theory even before it had been fully developed by Heisenberg, Schrödinger and their contemporaries. In 1922, he received a paper from Satyendra Nath Bose, an unknown Indian physicist. Bose had worked out the statistics of how a large number of photons would behave. Because photons are identical particles which do not interfere with one another, their behaviour is different from anything anyone had seen before. Indeed, Einstein realised that Bose had made a few small mistakes. He also realised that atoms, if cooled to close to absolute zero, would exhibit the same behaviour as photons. In fact, they would act like one giant atom. This prediction was thought outlandish at the time—and it was not until 1995 that the first so-called Bose-Einstein condensate was made in a laboratory. Investigating these condensates is now one of the most active fields of experimental physics.

This is but one more example of Einstein's prescience, seeing things no one else saw at the time. As he said in 1932, “the real goal of my research has always been the simplification and unification of the system of theoretical physics.” He never succeeded in unifying physics, but he did, much as it may seem paradoxical to the layman, succeed in simplifying it. Once one learns the complex mathematical language required to express his ideas, Einstein's theories are the simplest and most obvious of any in physics.