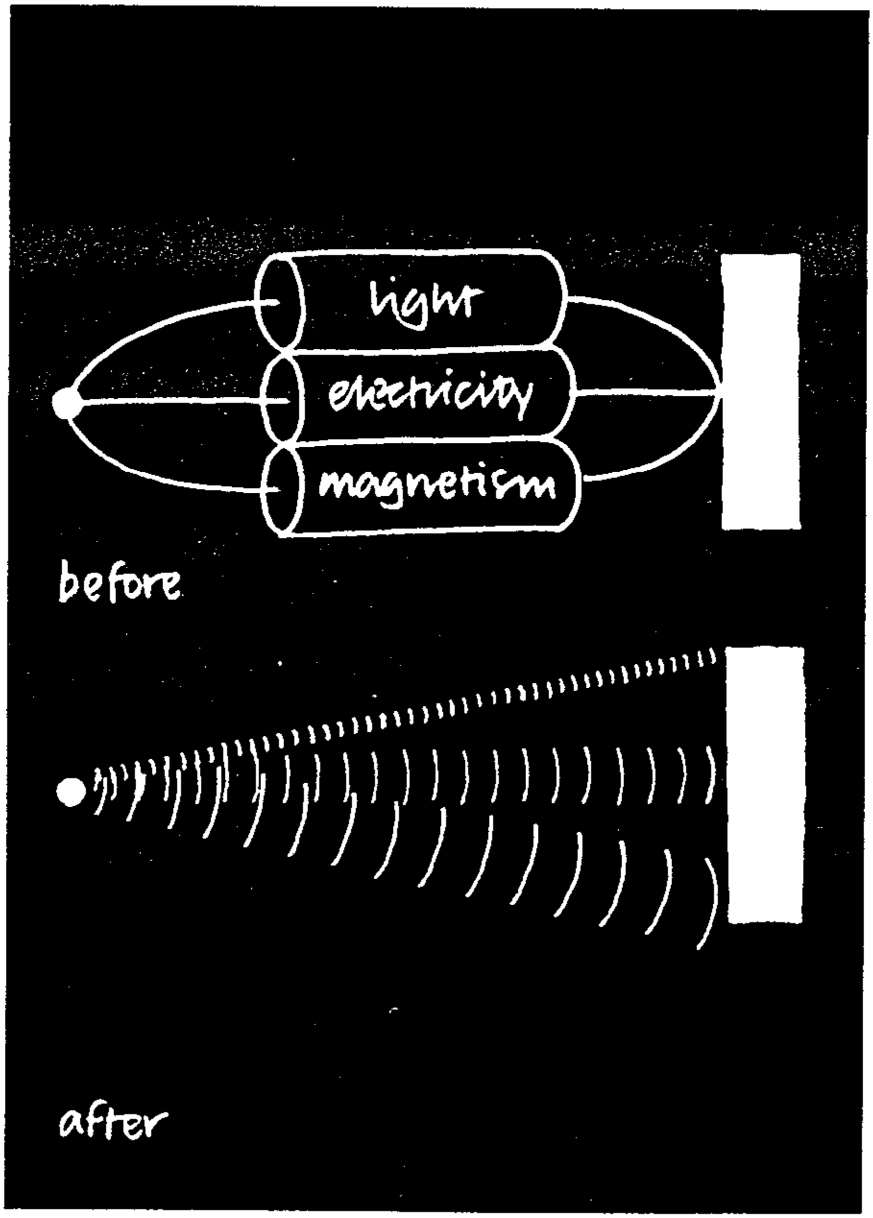
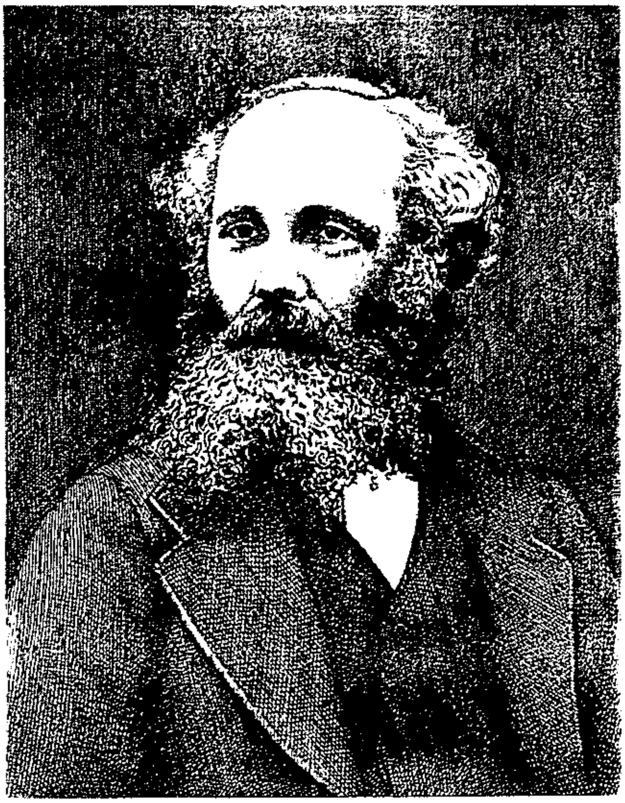
Clerk Maxwell

Before Clerk Maxwell people could study the effects of light, electricity and magnetism but had no idea as to their nature. By the applied power of his thinking he deduced that they were all electromagnetic waves obeying exactly the same laws but of different wave length. He even went on to explain the behaviour of types of radiation (X-rays, radio-waves) which had not then been discovered.

1831-1879



A theoretical physicist of consummate mathematical skill and imaginative power



Whimsical versifier, pious Victorian, subtle philosopher, capable administrator, ingenious experimenter, James Clerk Maxwell was above all a theoretical physicist of consummate mathematical skill and imaginative power. His theory of the 'electromagnetic field' was the crowning achievement of nineteenth-century physics, uniting in one conceptual scheme a vast range of phenomena previously thought to be unrelated, and leading directly to technologies profoundly influencing life today.

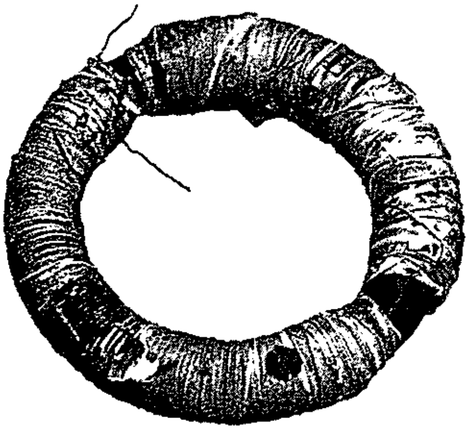
He was born in 1831 into a prosperous family of Lowland Scots, and enjoyed a classical education typical of the period. Intellectual promise showed early, in intense curiosity about the workings of nature and the details of machinery. At fifteen he wrote his first paper, on a method for constructing certain geometrical curves. Thus began a dazzling career. His reputation grew, and it was soon said of him that his intuition was such that it was impossible for him to think wrongly on any physical problem.

Unlike Einstein, who was almost exclusively concerned with nature's deepest secrets in the form of her most fundamental laws, Maxwell's scientific interests were astonishingly wide. In a series of experiments on colour vision he established beyond doubt what had previously been conjecture, that normal eyes contain three different types of colour sensitive receptor, and that in colour-blind people one of these types of receptor is missing. In a paper 'On hills and dales', he gave mathematical precision to the description of features of landscapes (watersheds, river basins, etc.). In an intricate work of theoretical astronomy, he proved that the rings of Saturn must consist of vast numbers of small sparsely-distributed solid particles; any other arrangement, such as rigid solid discs or thin rings of fluid, he showed to be unstable.

He significantly advanced the development of the atomic theory. In Maxwell's day there was no direct evidence for the existence of atoms. However, John Dalton had argued that the facts of chemistry strongly supported the ancient idea that matter was built up from irreducible structural units, rather than being a 'continuum' that could be indefinitely subdivided. Therefore attempts were made to explain the large-scale behaviour of matter as the result of the microscopic motion of its atoms. Pressure, for example, arises from the impacts of vast numbers of atoms, like rain drumming on a roof. Previous theories were hampered by ignorance of the nature of atomic motion, and the crude approximation had to be made that the atoms all travelled with the same speed. Maxwell realized that this could not be true in a situation where atoms experienced frequent collisions, and by an argument of remarkable simplicity he obtained a description of the way in which different speeds are distributed among the atoms, on the average. This result enabled him to make successful predictions about matter in bulk, in particular the friction (viscosity) of flowing gases.

All this would have made him a great scientist, but what makes him a god in the physicists' pantheon is his unified theory of electric and magnetic effects, which gave precision to the concept of the 'field'. To understand this it is necessary to go back almost two centuries before Maxwell, to Newton's theory of gravitation. This is based on 'action at a distance' – instantaneously, across a vacuum, matter tugs at matter – a magical idea which Newton himself certainly found deeply mysterious. All doubts were however soon dispelled by the striking success of applications of gravitation theory to astronomy. Any theory that could explain the intricate clockwork of the heavens with such precision had to be correct.

Left: James Clerk Maxwell: an engraving by Delzers.
Right: Faraday's electro-magnet.



and it was confidently expected that action at a distance would be a paradigm for the future development of physics.

And so it turned out. First electrified bodies, and then magnetized bodies were found to interact according to laws very similar to Newton's. The force between two such bodies, as measured by the mutual acceleration it produces in them, depended on the amount of electric charge and the strength of magnetization, and diminished as their distance apart increased. There was one difference: unlike gravity, electric and magnetic forces could be repulsive as well as attractive. But this did not alter the fact that here were two more substantial aspects of the physical world that could be understood in terms of action at a distance.

At first, electricity and magnetism were thought to be unrelated. Then in 1820 Hans Ørsted found that an electric current – that is, a flow of electrically charged particles – deflected the needle of a magnetic compass. Therefore electric charges could, if they were moving, produce magnetic effects. Faraday quickly discovered another connection, his 'law of induction': changing the distance between a magnet and an electric circuit caused a current to flow. This led to the developments of the electric motors and generators that dominate our technology today. The new science of electromagnetism was emerging. What were its fundamental laws? To describe the new interactions of electric charges with magnets clearly required an action at a distance more complicated than that of gravitation. The search for the new laws was beset with immense mathematical complications.

Faraday was not a mathematician, and his response to these difficulties was to develop a vivid pictorial language to describe electromagnetics. Ultimately this involved action at a distance, but it introduced the intermediate concepts of electric and magnetic 'fields'. A magnet, say, was supposed to fill the region around it with 'lines of force'. The direction of line at any point gave the direction of the force that would act on the north pole of a second magnet brought there, and the crowding of the lines would indicate the strength of the force. This pattern of lines of force in space was what Faraday called the magnetic field. He defined the electric field in a similar manner. The fields surrounding charges and magnets could be explored by measuring the forces on small 'test' charges and magnets placed at different points in the field. Although the fields were only mental crutches, auxiliary devices for calculating the mutual interactions between bodies, Faraday soon came to think of them as physically real conditions. The lines of force were tensions existing in space even when there were no 'test bodies' to measure their strength. The idea was a fruitful one. For example, Faraday's own law of induction could be stated as follows: a changing magnetic field (produced by moving a magnet) gives rise to an electric field (that urges a current round a wire placed in it).

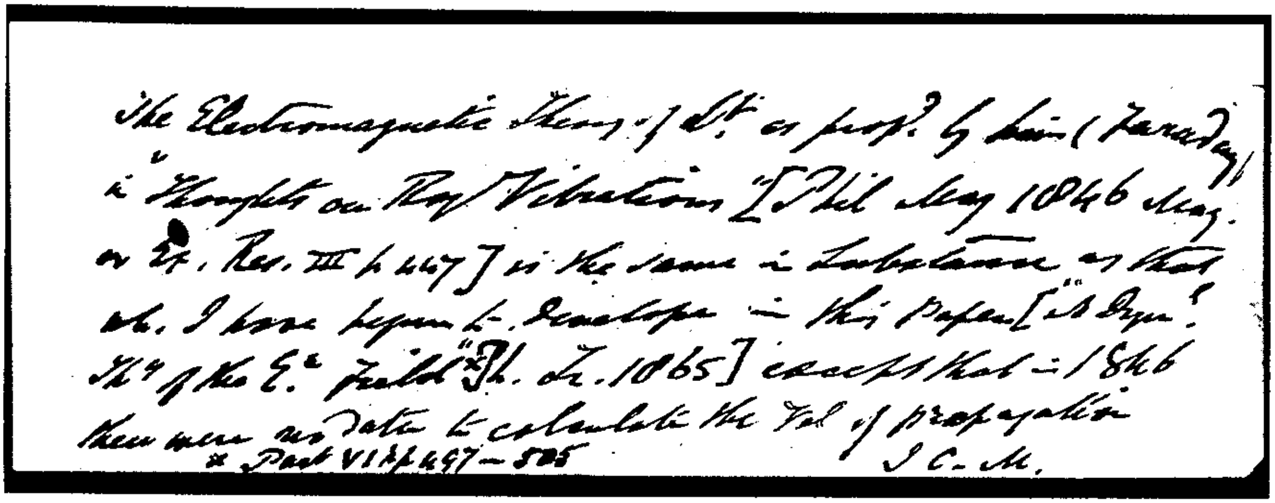
Maxwell saw the power of Faraday's ideas and in the early 1850s set himself the task of giving them precise mathematical expression. Instead of seeking the generalized law of action at a distance, he sought the laws governing the electromagnetic field. That is, he wanted to know how from a given set of charges and magnets, moving in given ways, he could calculate the electric and magnetic fields in the surrounding space. To his surprise, he discovered that the existing laws were inconsistent with one another: to complete the logical structure of electromagnetism, there had to be some hitherto unsuspected relation between electricity and magnetism. The 'field' point of view made it possible to discover this missing link. Maxwell argued that since changing magnetic fields produce electric fields even though no charges or batteries are present, so should changing electric fields produce magnetic fields even if no magnets are present.

This is typical of the kind of argument used by theoretical physicists. It is based on the ultimately metaphysical principle that the laws of nature are as symmetrical as possible. Unfortunately the technology of the time was inadequate to test Maxwell's proposed new law directly. However, Maxwell soon found that it enabled him to write down equations for the electromagnetic field that were symmetrical and free of inconsistency. These equations had a remarkable property: electric and magnetic disturbances do not travel at infinite speed, as had been predicted on the previous 'action at a distance' theories. Instead, any change in the arrangement of a group of charges and magnets produced an 'electromagnetic wave' expanding into the surrounding space with a definite speed. This speed could be calculated using existing data from electric and magnetic measurements. It turned out to be precisely the known speed of light!

The inference was irresistible that light is an electromagnetic wave, a set of linked oscillating electric and magnetic fields travelling through space. This was a great unifying moment in physics. Such a fundamental connection between optics and electromagnetism was quite unsuspected. It had been known for half a century that light was a wave motion, and the term 'ether' had been given to the space-filling medium that was supposed to be oscillating. Now it appeared that the same ether was the medium whose tensions were described by Faraday's lines of force. Maxwell made an elaborate mathematical model of the ether as a system of cogwheels filling space. This 'represented' the ether in the same way that Faraday's fields 'represented' the laws of action at a distance. Maxwell however did not claim that his cogwheels

A cornerstone of theoretical physics

Maxwell's handwritten notes on Faraday's 'Thoughts on Ray Vibration'.



The Electromagnetic Theory of Lt as propd by him (Faraday)
in "Thoughts on Ray Vibrations" [Phil Mag 1846 May.
or Exp. Res. III p 447] is the same in substance as that
wh. I have begun to develope in this Paper ["A Dynl
Thy of the E.c Field" *Ph. Tr. 1865] except that in 1846
there were no data to calculate the vel of propagation
* Part VI pp 497–505
J.C.M.

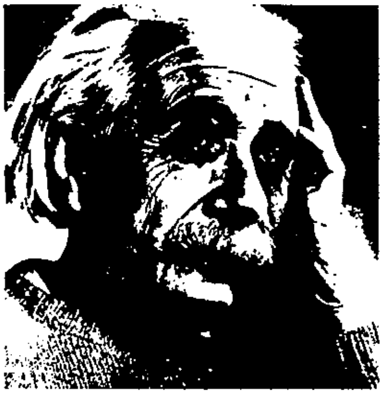
actually existed; he knew that the model was merely one of many possible models, and that his theory really depended on the truth, or otherwise, of his field equations as a description of nature. In this he was the first clear exponent of the method of modern theoretical physics: detailed models may be useful in suggesting new sets of fundamental equations, but it is the equations themselves, and not the models giving rise to them, that really count.

The wavelike fields that appeared as the solution of Maxwell's equations could have any wavelength, and it was obvious that visible light, whose wavelength is about a two-thousandth of a millimetre, is just a special case, important to us because our eyes happen to be sensitive to it. There should exist a whole gamut of radiations – the 'electromagnetic spectrum' – consisting of waves all of which travel at the same speed. Shortly after Maxwell's tragically early death in 1879, Hertz detected waves produced by purely electrical means and thus provided conclusive evidence for the correctness of the electromagnetic theory. 'Hertzian waves', centimetres to kilometres in length, form the basis of radio, television and radar communication. At the shortwave end of the spectrum, there are X-rays – the size of atoms – and gamma rays – the size of the nuclei within the atoms. The ethereal music that Maxwell produced by 'symmetrizing' the equations of electromagnetism currently encompasses about twenty octaves.

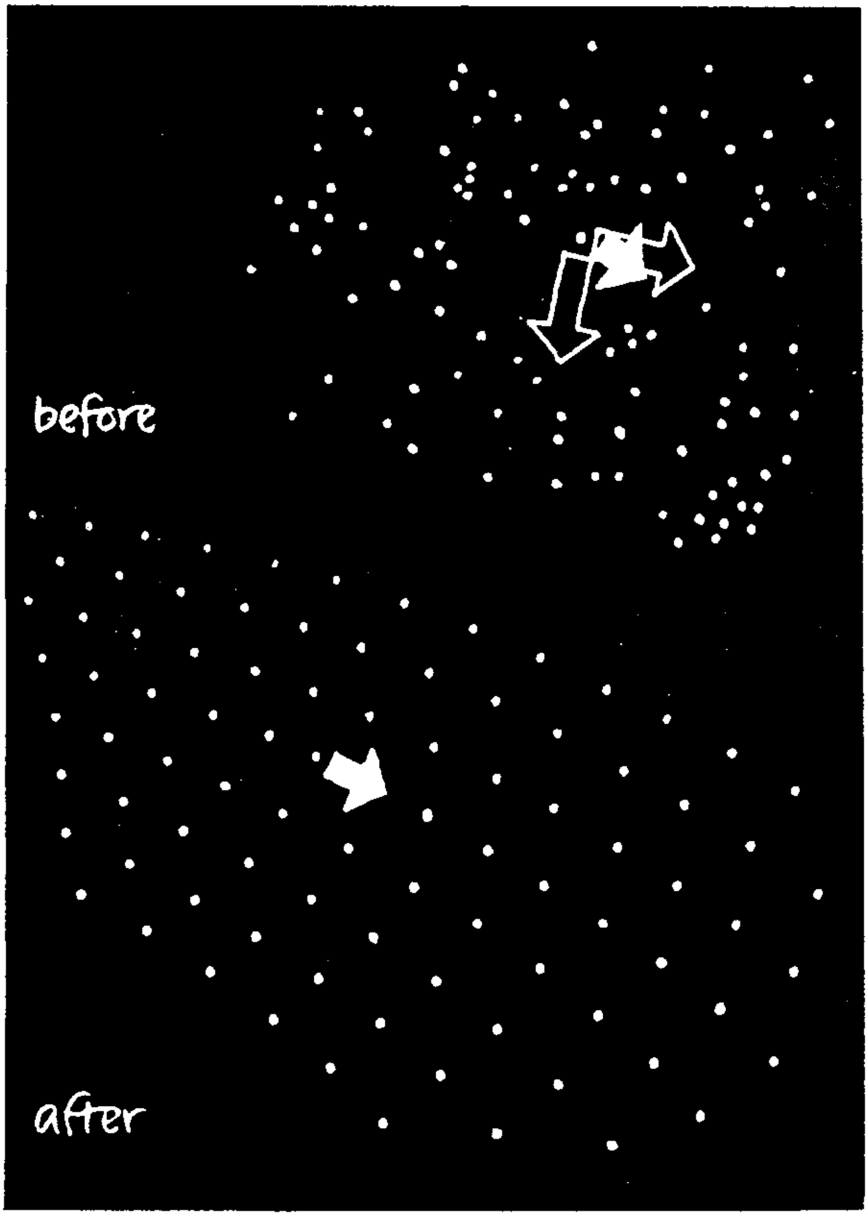
Maxwell's equations apply on cosmic scales and also within atoms. Only on the very finest scales do the effects of quantum mechanics appear, barely detectable by our most delicate instruments. Einstein showed that Maxwell's electromagnetism was inconsistent with the mechanics of Newton. This meant that no 'cogwheel' model of the ether could possibly be correct. But Maxwell's equations themselves remained valid; it was Newton's laws that needed modification. It is possible to reformulate Maxwell's theory in terms of action at a distance between bodies, but that action must be 'retarded' to allow time for the waves to travel; the resulting laws are complicated and not widely used. And so, after more than a century, Maxwell's unified theory of the electromagnetic aspects of nature is still a cornerstone of theoretical physics. M.B.

Einstein

Einstein shattered the traditional concepts of space, time, energy and matter. He showed that instead of moving with Newtonian motion through a neutral space, objects moved through a space-time continuum which could itself be curved. The implications of his theories led directly to the development of nuclear energy.



1879-1955



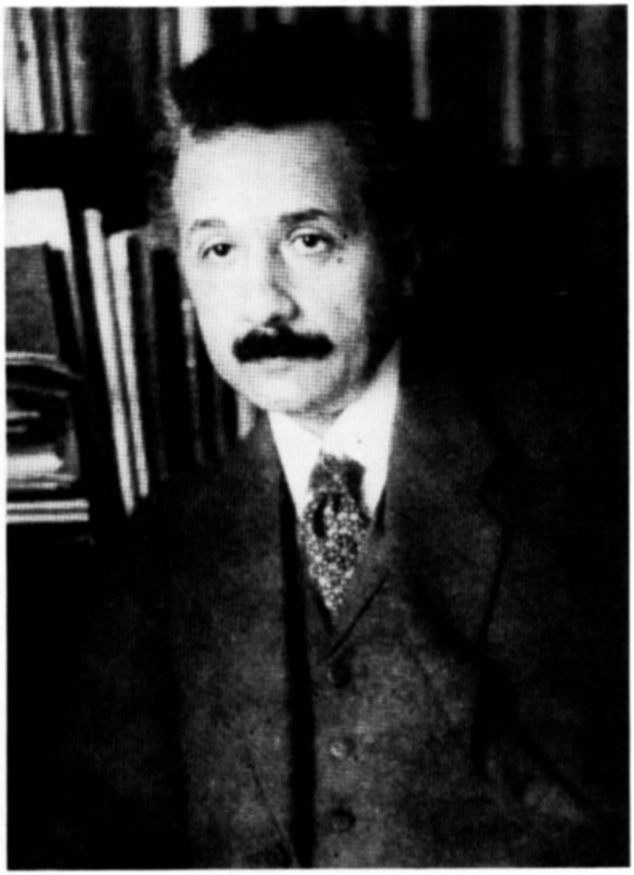
In 1895, at the age of sixteen, Albert Einstein wrote a letter to his uncle, in which he wondered what would be seen by someone travelling so fast that they could catch up with a light ray. Ten years later he solved the problem, in the first of a series of thunderbolts that exposed profound inconsistencies in the system of fundamental physical laws inherited from the nineteenth century. Meanwhile, this cosmopolitan young man (who had already lived in Germany, Italy and Switzerland) had a traditional education that left him with a lifelong hatred of all forms of authority. His university career was undistinguished, and despite boundless confidence and a constant dreamlike absorption in his subject he found himself unable to find employment as a physicist. Instead he got a job as a technical officer with the Swiss Patent Office in Berne. The work was not heavy, and he was able to devote his evenings to the deepest problems of physics and returned to the problem of that light ray.

Forty years earlier, Maxwell had shown that light was a travelling pattern of electric and magnetic fields – an 'electromagnetic wave'. Einstein thought at first that if he caught up with the light he would see a static pattern of fields, rather as a surf-rider sees a static disturbance on water while those on shore see a travelling wave. The trouble was that Maxwell's equations could not be made to yield any solution that corresponded to these static fields: the waves had always to travel at the same speed. Perhaps Maxwell's theory applied only to observers at rest relative to the 'ether' in which light was thought to travel. But A. A. Michelson and E. W. Morley, a few years before, had measured the speed of light in different directions with apparatus moving at different speeds. They found that however the observer was moving the speed of light was always the same. This was a triumph for Maxwell's theory, but a disaster for common sense. If you chase after a light ray, how can its speed fail to diminish, as measured by you?

Einstein took the Michelson-Morley result seriously, as showing that Maxwell's theory gives a valid description of light no matter how fast the observer is moving. He did not worry about contradictions with 'common sense' – after all, the speed of light was uncommonly faster than anybody had travelled at that time, and common sense was no guide in such a situation. Instead, he analyzed the logical consequences of never being able to catch up with the light. Consider two events: the emission of a flash of light and its reception after reflection from a distant mirror. Einstein showed that the time interval between these events, and the distance between them, would be different when measured by observers who were moving relative to one another, even if the observers used identically constructed clocks and rulers.

This was shattering. All of physics was thought to be consistent with Newton's laws of mechanics, and these in turn were based on the assumption that times and distances between events were absolute, that is, independent of the speeds of observers measuring them. Einstein's result showed Maxwell's electromagnetism to be inconsistent with this, and the Michelson–Morley experiment suggested that it was Newton who was wrong. Newtonian mechanics had to be replaced by something; there had to be some way of predicting how objects move in response to forces acting on them. Moreover, the old theory had been staggeringly successful for over two hundred years in astronomy and engineering, so the new theory had to give virtually the same predictions at low speeds;

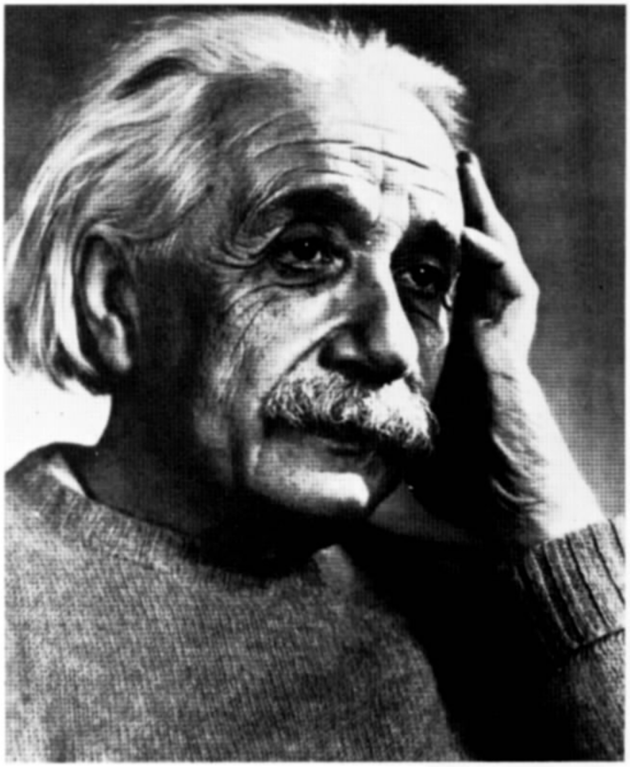
Einstein at the time of the publication of his 'special theory of relativity', 1905.



only for relative motion near the speed of light could there be differences.

Einstein was able to devise a new mechanics satisfying these conditions and consistent with Maxwell's theory of light. One conclusion was that, as an object moved faster relative to an observer, it became increasingly difficult to accelerate it further – in effect the mass of the body increased with its speed, becoming infinite at the speed of light. Thus this speed is a natural limit which no material object can attain: once again, it is impossible to catch that ray of light. Another conclusion was that the mass of a body – even one at rest – must be regarded as a form of energy. In mathematical terms, the energy (E) locked up in an object is related to its mass (m) and the speed of light (c) by the famous equation:

$$E = mc^2$$



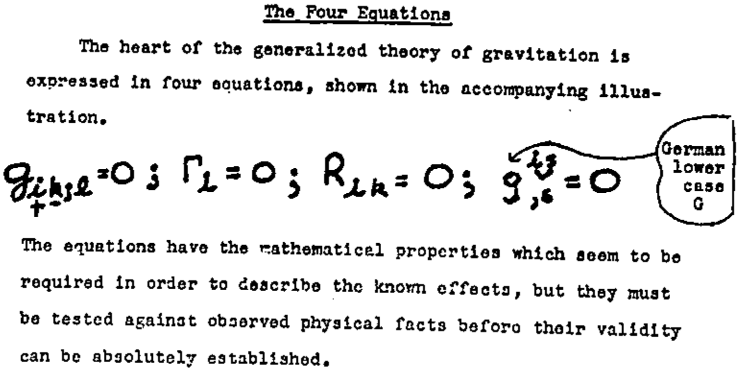
Nuclear reactions in the sun convert mass into energy at a rate governed by this equation; the energy comes to us as sunshine while the sun loses mass in proportion. Our own nuclear technologies of power generation and mass destruction are based on the same equation. All the other predictions from Einstein's mechanics, as well as the astonishing relationships between times and distances as measured by different observers, are abundantly confirmed every day by the swiftly-moving subnuclear particles produced in nuclear accelerators.

So far we have discussed what is called Einstein's 'special theory of relativity', completed in 1905. It is a theory of 'relativity' because it gives a consistent description of motions, distances etc, as measured by different observers whatever their *relative* motion. It is 'special' because it shares with Newtonian mechanics two difficulties, both connected with gravitation. Einstein spent the next ten years devising a 'general theory of relativity' which would overcome these problems. The first concerns the unique nature of the motion produced by gravity: all bodies fall with the same acceleration – a man and a motor car, pushed off a cliff together, will hit the bottom together. This was known to Galileo, and of course Newton took account of it. But other forces do not act in this way: for example a source of electric force, a charged body, may repel or attract other bodies in different ways depending on their masses and electric charges. In Newtonian mechanics and also in special relativity, however, the peculiar nature of gravity was only partially included, by making the 'inertial mass' that governs a body's resistance to motion under the action of forces the same as the 'gravitational mass' that governs its response to gravity. No explanation was given for this remarkable fact.

To appreciate the second problem, carry out the following experiment: stand outside on a starry night and look up. Let your arms hang limply by your sides. Then spin around rapidly. At once two things happen: the stars rotate, and your arms rise up almost to a horizontal position. It is impossible to believe that these effects are unconnected, but Newtonian mechanics and special relativity fail to specify the manner in which the stars' gravitation affects rotating bodies.

Einstein's bold solution to these problems was perhaps the greatest triumph ever achieved by the disciplined imagination. Imagine a laboratory falling freely under gravity (among the stars, say, or in an orbit around the sun). Within that laboratory no gravitational effects can be detected ('weightlessness') and the special theory of relativity gives a correct description of all experiments conducted there. On a larger scale the laboratory pursues a trajectory through space and time ('spacetime') in the

Right: Part of Einstein's paper on his 'generalized theory of gravitation' completed in 1949.
Opposite: In 1933 Einstein emigrated to America where he spent the last years of his life.



The Four Equations

The heart of the generalized theory of gravitation is expressed in four equations, shown in the accompanying illustration.

$$g_{\underset{+\,-}{ik};l}=0\,;\quad \Gamma_{i}=0\,;\quad R_{ik}=0\,;\quad \mathfrak{g}^{\underset{\vee}{ik}}{}_{,s}=0$$

The equations have the mathematical properties which seem to be required in order to describe the known effects, but they must be tested against observed physical facts before their validity can be absolutely established.

shortest possible time as measured by its own clock. Thus, in some sense, motion under gravity is the 'straightest' possible. In that case, why do orbits never close up on themselves, as the earth's does? Because spacetime is *curved*. The four-dimensional nature of spacetime (three for space, one for time) makes this impossible to visualize except by analogy: a 'shortest' line on a curved surface (e.g. the earth's) can bend. Strictly any such analogy is unnecessary, because Einstein's equations alone are sufficient to predict orbital motions once the cause of the curvature of spacetime is identified. It is *matter* that produces curvature – near a star, spacetime is warped, so that the shortest lines can bend. Thus on this theory gravitation emerges not as a special force but as a property of the geometry of spacetime itself, in which objects pursue the simplest possible motions.

Conceptually, 'general relativity' is completely different from Newtonian theory. Instead of absolute space and absolute time providing a passive arena in which events can happen, the very structure of spacetime is determined by the bodies in it, while at the same time it determines the trajectories of these bodies. Yet its predictions are in most cases identical to Newton's. Only for strong gravitational fields (e.g. near the sun) do the two theories differ. Einstein predicts that light should be delayed and bent when passing close to the sun, that light emitted by the sun should be slightly reddened as a result of having to climb out of the gravitational field, and that the form of the orbits of the planets closest to the sun should be slightly altered. All these effects have been observed, and the measurements favour Einstein and not Newton.

Gravitation is the dominant force in the universe on large scales, and it was natural that Einstein's theory would be applied to cosmology. The combined effect of all the galaxies is to produce an overall curvature of spacetime, and the equations show that the resulting universe cannot be static: it must either be expanding or contracting. In fact E. P. Hubble's observations of the 1920s showed that it is expanding. In recent years, under the impetus provided by radio astronomy, cosmology has become a rapidly-developing branch of science. Its principal theoretical tool remains the general theory of relativity.

The evolution of stars is governed by gravity, and the astrophysical application of Einstein's theory predicts that the ultimate fate of any star more than a few times heavier than the sun is complete collapse under its own weight. When during this collapse the star shrinks below a certain size then, although it will continue to exert gravitational effects, no light can escape from its surface and the star ceases to be visible. Such collapsed objects are called 'black holes'. At the time of writing several objects have been tentatively identified as black holes by their effects on neighbouring visible stars.

It can be convincingly argued that great theories in science 'emerge' when the intellectual climate is right. If Newton, Maxwell and Einstein had never lived, it is probable that others would have devised the theories of mechanics, electromagnetism and special relativity. But general relativity is an exception: the problem and its solution came entirely from Einstein, and if he had never lived it is possible that the theory would still not have been invented.

Einstein's scientific achievements were not confined to relativity. He also led the attempt to discover the laws governing matter on subatomic scales: the mysterious 'dual' nature of light, which behaves like waves when travelling through space and like particles ('photons') when being absorbed or emitted by matter. It was his formulation of the laws of absorption and emission that eventually led to the invention of the laser. However, the final synthesis of this part of physics, the theory of quantum mechanics, came not from Einstein but from Erwin Schrödinger and W. K. Heisenberg. According to this theory, it is impossible to predict the detailed motion of atomic systems: only statistical knowledge is possible, in the form of probabilities. Einstein never accepted that there could be such fundamental limitations to our knowledge of the world. Certainly quantum mechanics was spectacularly successful in explaining the facts of chemistry and the behaviour of solid matter, but Einstein, increasingly isolated as his fellow physicists became absorbed in applications of the new theory, maintained for the rest of his life that: 'God does not play dice with the world.'

From the success of his general theory of relativity until his death in 1955 Einstein lived in the glare of publicity. At first he was simply the eccentric genius who never wore socks. Then he became the champion of Zionism, passionate pacifist and opponent of rearmament. As the Nazis tightened their grip on Germany he saw that they could only be resisted by force, and he abandoned pacifism to the extent of advising President Roosevelt of the possibility of making atomic bombs. When the weapons were actually used on Japan he immediately advocated the establishment of a world authority which would control all weapons of mass destruction. It is hard to prove that any of these various political actions had a significant influence on the turbulent history of the times through which he lived. But even if Einstein the humanitarian may soon be forgotten, Einstein the physicist has already joined the immortals. M.B.