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by Petros S. Florides

Two of the most profound physical theories that dominate the present-day scientific world are, undoubtedly, the theory of relativity and quantum theory. Both theories are the outcome of two scientific revolutions which shook the world of physics at the beginning of the twentieth century. Both revolutions were to alter, radically and irrevocably, our fundamental physical and philosophical concepts of our world, from the ultimate constitution of the atom to the structure and evolution of the universe.

The *sole* architect of the first revolution, which led to the theory of relativity, was Albert Einstein. One of the *chief* architects of the second revolution, which led to the quantum theory, was, again, Albert Einstein. This is the man to whom, on this hundredth anniversary of his birth, this article is humbly dedicated.

In an era adorned by some of the greatest grand masters of theoretical physics that ever lived, Einstein was the supreme and undisputed champion. His fellow physicists hailed him as the greatest physicist of his time and, possibly, of all time. They revered him and, those who were fortunate to come in touch with him, literally loved him just as much for his intellectual powers as for his charisma: for the unparalleled originality of his ideas and the clarity and simplicity with which he expressed them; for his gentleness, his generosity, his humour, his unassuming manners and for his concern for humanity. He was an ardent advocate of freedom, democracy and world government, and a vehement opponent of Nazism. He changed his dearly-held pacifist views only in the face of the impending Nazi menace in the early 'thirties. He changed his strong anti-nationalist views to become a staunch supporter of Zionism in the face of the merciless persecution of his fellow Jews.

But what was Einstein's magic that fired to such an extent the imagination of millions of ordinary people all over the world? The answer must partly lie in the overzealous reporters and scientific popularizers who, never hesitating to mix fiction with fact for greater effect, presented Einstein as a mathematical wizard who created a kind of Alice-in-Wonderland world, a world of four dimensions, a world in which bodies shrink in the direction of their motion and in which time can stand still; a world in which the rays of light are bent, and space and time are warped, and so on, and so on. Yet the most elaborate and accurate experiments and observations reveal that this seemingly fantastic world that Einstein created is remarkably similar to the real world we live in. Another reason for this mystical response of the public was the general belief that Einstein's theory of relativity was mathematically so complex that only a handful of mathematicians could understand it. This is aptly summarized in the following story. Early in the 1930s, when Einstein visited Los Angeles, Charlie Chaplin went to the station to meet him and then drove him around Hollywood to the ecstatic cheers of thousands of people who lined the streets. The wise beggar turned to Einstein and said: 'You see, they are cheering me because everybody understands me, they are cheering you because nobody understands you.'

There is no doubt that a thorough understanding and appreciation of the theory of relativity presupposes an extensive knowledge of advanced and sophisticated mathematics. My only aim in this article is to sketch the origin of the theory of relativity and highlight some of its consequences. In doing this we shall not lose sight of Einstein the man.

Albert Einstein was born on 14 March 1879 in the city of Ulm in Southern Germany. Albert's parents, Hermann and Pauline Einstein, were Jewish and by all accounts were a devoted and happy couple. They were not typical Jews in that they were entirely areligious and retained but little of their Jewish customs. Furthermore, father Hermann was an unsuccessful businessman throughout his life. When Albert was a year old the Einsteins moved to Munich. There Hermann and his brother Jacob went into business together setting up a small electrotechnical factory. For their elementary education the Einsteins sent their children, Albert and Maja, to the nearby Catholic school. Their education in Judaism was not, however, neglected. It was during these school years that young Einstein became intensely religious, in spirit and in ritual. It was, as we shall see, a short lived experience. As a child Einstein showed no sign for any special talent. On the contrary his parents were concerned that he might be subnormal, for he could barely speak until he was three and he still spoke poorly at the age of nine. He was a shy and dreamy child and he was dubbed 'Father Bore' by his nurse.

Despite these early drawbacks, or because of them, Einstein's inborn curiosity about the nature of things emerged at an early age. The most vivid impression that Einstein preserved from childhood was his observation, at the age of four or five, of the behaviour of the magnetic compass. The fact that a magnetic needle, although isolated and inaccessible, was always pointing in the same direction came to him as a revelation. In his autobiographical notes the ageing Einstein wrote: 'I can still remember—or at least I believe I can remember—that this experience made a deep and abiding impression on me.' At the age of six Einstein began to learn the violin. Music and, later on, sailing were to remain the two passionate hobbies throughout his life.

Einstein's gift for mathematics came to the fore at the age of ten when his uncle Jacob, an engineer by profession, began giving Einstein informal lessons in algebra and geometry. When he was told of the Pythagorean theorem he was so fascinated that, though unaware at this stage of the intricate logical structure of Euclidean geometry, he was able, after some hard work, to prove the theorem his own way. When at the age of twelve uncle Jacob presented Einstein with his first textbook on Euclidean geometry his fascination must have been incomparably greater. In his autobiographical notes Einstein refers to this textbook as 'the holy geometry booklet' and says that the 'lucidity and certainty' with which the theorems were proved 'made an indescribable impression on me'. At this stage Einstein was already in the (Luitpold) Gymnasium—the equivalent of the secondary school—which he joined at the age of ten.

Alongside the 'holy geometry booklet' Einstein was also reading avidly popular books on science. As a result he soon reached the conviction that much in the stories of the bible could not be true. We let Einstein take up the story: 'The consequence was a positively fanatic orgy of free-thinking coupled with the impression that youth is intentionally being deceived by the state through lies; it was a crushing impression. Suspicion against every kind of authority grew out of this experience, . . .' This suspicion against authority was, no doubt, instrumental in the development of the powerful independence of mind that enabled him to challenge so many long established scientific beliefs. In old age Einstein was to say, 'to punish me for my contempt for authority, Fate made me an authority myself'.

The outcome of the 'crushing impression' mentioned above was that Einstein became, and consistently remained, an 'agnostic' throughout his life. Einstein always referred to 'God', or 'the Good Lord', or the 'Old One', and so on. But this was unlike anybody else's God. Einstein looked at the world with curiosity and an intellectual desire to apprehend it. He was convinced, almost with religious fervour, that the world, with all its wonders and mysteries, forms a meaningful picture which can be understood. 'The most incomprehensible thing about the world is that it is comprehensible', he once said. He was also convinced, again with religious fervour, that this world picture can be understood on the basis of a limited number of principles, or laws, which to some extent at least, the human intellect can unveil. In this respect he was the worthiest beneficiary of the legacy left to us by the ancient Greek philosophers. This conviction of an ordered and comprehensible world formed Einstein's God. This is the God he meant when he said, 'God is subtle but he is not malicious'. When in the 1930s Rabbi Herbert Goldstein of New York cabled Einstein with the question 'Do you believe in God?', Einstein cabled back, 'I believe in Spinoza's God, who reveals himself in the harmony of all being, not in a God who concerns himself with the fate and actions of men.'

Einstein's years in the elementary school and in the Gymnasium were anything but happy. He disliked immensely the ruthless discipline and the harsh rote method of instruction. He was to remark later on that, 'the teachers in the elementary school appeared to me like sergeants, and the Gymnasium teachers like lieutenants.'

In the meantime the small factory of Hermann and Jacob Einstein was entering hard times. In 1894 the two families moved to Italy where they set up a factory in Pavia (near Milan). Young Einstein, then 15 years old, was left behind to finish his school year at the Gymnasium. But no sooner had his parents left than Einstein was contemplating and making secret plans to leave the Gymnasium and join his parents. His task, however, became easier when his home-room teacher (his teacher of Greek who prophesied that Einstein would never amount to anything) told him that it would be desirable if he were to leave the school. To Einstein's remark that he had done nothing amiss the teacher replied, 'your mere presence (in the class) destroys the respect of the class for me'. Soon Einstein was with his parents. His first act was to renounce his German citizenship. He was to remain stateless for six years until he became a Swiss citizen at the age of 21.

His stay in Italy was extraordinarily happy. Overwhelmed with his new-found freedom he roamed the countryside, he visited museums, galleries and concert halls and he was systematically studying mathematics on his own. But the Einsteins' business was once again entering hard times and young Einstein had to look to the future. In 1895, at the age of sixteen and a half, he took the entrance examinations to enter the famous Polytechnic in Zurich. He failed! But he must have done brilliantly in his mathematics and physics papers. For the professor of physics, Heinrich Weber, took the unusual step of having Einstein told that he could attend his physics lectures. Einstein, however, took the advice of the director of the Polytechnic (an equally unusual step on behalf of the director) and spent the following year studying for the diploma of the progressive Swiss cantonal school of Aargau in the town of Aarau. Equipped with the diploma Einstein was able to enter the Polytechnic, in 1896, without any further examinations. He took the course for training specialist teachers in mathematics and physics.

Einstein was not what we may call a model student. What did not interest him he found hard to study. He attended lectures, even professor Weber's lectures, only fitfully and with little enthusiasm. He preferred to study the great works of science and philosophy on his own. It wasn't long before he alienated his professors. Professor Weber was to say to him: 'You're a clever fellow! But you won't let anyone tell you a thing. You won't let anyone tell you a thing.' But in his four-year course there were two 'days of reckoning' on which Einstein had to pass two major examinations. With such poor attendance and hardly any lecture notes failure would have been inevitable. The impending danger of disaster was, on each occasion, narrowly averted with the help of his classmate, and later his life long friend, Marcel Grossman. Grossman was a brilliant mathematician who was as meticulous in attending lectures as taking clear and detailed notes. Thanks to these notes Einstein was able to graduate at the Polytechnic in 1900. He was, then, 21 years old. The hunt for a job was now on. He was looking for a university post, but without any satisfactory testimonials from his former professors he could find none. In 1901 he wrote: 'From what people tell me I am not in the good graces of any of my former teachers', and, 'I would long ago have found [a position as assistant in a university] had not Weber intrigued against me'. For two years after graduation Einstein was to earn his living by tutoring and by temporary jobs in schools.

In 1901 Einstein published his first two research papers (one on capillarity and the other on thermodynamics) in the prestigious scientific journal *Annalen der Physik* (the second paper was unsuccessfully submitted to the university of Zurich as a doctoral thesis). But still no job. As in his undergraduate days his friend Grossman, now a mathematics assistant in the university of Zurich, came to the rescue. With his help Einstein finally secured a job as an examiner of patents in the Swiss Patent Office in the city of Bern. He started work on 23 June 1902 as a probationary Technical Expert, Third Class. Einstein was forever indebted to Grossman for his help in securing this job. In the last year of his life he wrote that it was 'the greatest thing that Marcel Grossman did for me as a friend'. Einstein had good reasons for being indebted to Grossman. For it was within the walls of the Swiss Patent Office that his genius matured. The job was not demanding and Einstein used to do a lot of his own research even during working hours.

In 1903 Einstein married Mileva Maric (of Serbian origin) who was his class mate at the Polytechnic. They had two sons but apparently, little else in common; they were separated in 1914 and finally divorced in 1919.

From 1902 to 1904 Einstein published three more papers on statistical mechanics and thermodynamics, again in the *Annalen der Physik.* Working full time in the Patent Office, almost totally isolated from the scientific community and with hardly any scientific references accessible to him, little did Einstein know that in these papers he was covering ground already explored by the Austrian physicist Boltzman and ground which, to some extent, was being explored, almost simultaneously with him, by the American scientist Willard Gibbs. The deep understanding and novel approach to thermodynamics and statistical mechanics shown in these three papers revealed Einstein as the 'master of statistical reasoning'.

Important as his early papers were, they were just a sideline and a prelude to Einstein's main scientific theme. Exciting and far reaching ideas were brewing in his mind. The main theme opened with a deafening crescendo in 1905, the year in which Einstein's dazzling genius burst wide open. The 'miracle year', as it is sometimes called, the year 1905, saw the publication of *four* revolutionary papers, on *three* widely different topics, in the same journal, *Annalen der Physik*, volume 17, by the same man, Albert Einstein. He was then twenty-six years old. It has often been said that the most important requirement in research is to have an idea, the next most important requirement is to have *no* second idea. Einstein was to prove how utterly wrong this can be. He had, simultaneously, three spectacular ideas.

The first paper was entitled 'Heuristic viewpoint concerning the generation and transformation of light'. It re-introduced, in a sense, the corpuscular theory of light which Newton propounded in the seventeenth century, but with important differences. Einstein conceived of light as a stream of particles, called *photons*, each photon being endowed with a *frequency*, a sort of pulsation, which not only determines the colour of light but, also, its energy. In an era in which the wave theory of light reigned triumphantly, this was nothing short of heresy. Yet it explained hitherto mysterious phenomena, most notable among them the photoelectric effect, and was finally verified experimentally in 1916 by the American experimenter Robert Millikan. The irony was that Millikan's intention in performing his experiments was to demonstrate, once and for all, that Einstein's heretical theory of light was wrong. (It must be mentioned that it was this paper of Einstein's, together with Max Plank's famous paper of 1900, that sparked off the second revolution I mentioned at the beginning; it was the revolution that led to the development of quantum theory.) As a result of this work Einstein received the Nobel prize in 1922.

The second paper of 1905 is more commonly known as Einstein's paper on 'Brownian motion'. The paper explained, for the first time, the peculiar zig-zag motion of small particles suspended in a fluid, a motion which was first observed by the Scottish botanist Robert Brown some eighty years before. Above all, this paper demonstrated the existence of atoms so forcefully that even the most skeptical of the skeptics (Ostwald, Mach) were finally convinced of their reality. This paper Einstein submitted to the University of Zurich as a Ph.D. thesis (it was 'Dedicated to my friend Dr Marcel Grossman'). It was rejected on the ground that it was too short. Einstein added one single sentence, he re-submitted it and, finally, he became a Ph.D. in 1905.

We finally come to the third paper, 'Electrodynamics of moving bodies'. The theory which was propounded in this paper was to become known as Einstein's special theory of relativity. It was Einstein's first step on the road to fame and to immortality. We pause here to talk briefly about this theory. To appreciate the theory and its revolutionary character, and to set the scene for what follows for most of the rest of the article, I shall first sketch the state of physics, mainly classical dynamics and electromagnetism, prior to the advent of the special theory of relativity.

The foundations of classical (or Newtonian) dynamics were led down by Galileo and Newton in the sixteenth century. The theory was to reign supreme for about three hundred years with astonishing success in both terrestial and celestial mechanics. In the hands of the great mathematicians Euler, Lagrange, Laplace, Hamilton, and others, the theory reached such illustrious heights that it was considered, right down to the end of the last century, as the greatest and most permanent achievement of the human mind. It became the model theory which every other theory strove to emulate. Lagrange was to say, 'Newton was fortunate, because the science of our world can be created only once, and it was Newton who created it'.

The whole of Newtonian dynamics rests, mainly, on the following two laws which concern the motion of a particle:

1. *Law of inertia:* a particle acted on by no forces continues in its state of rest or uniform motion along a straight line.

2. *Law of motion:* $m\,\mathbf{a} = \mathbf{F}$
   where m is a characteristic of the particle called its *inertial mass*, $\mathbf{a}$ the acceleration of the particle and $\mathbf{F}$ the force acting on the particle.

Now it is a truism that the motion of a particle can be detected only as a *change of its position with respect to some other body.* This other body, relative to which the motion of a particle is described, is called a reference body or, more generally, a *reference system.* It can be taken to be the earth, a moving train, the sun, anything. It follows from what we have just said that, unless a reference system is specified, the two Newtonian laws of motion are completely devoid of any physical meaning. Newton, of course, was well aware of this and he himself introduced the concept of *inertial* reference systems. These are normally, though inadequately, defined as reference systems in which, or relative to which, Newton's laws of motion are valid. Any two of these inertial systems are in uniform translatory motion relative to each other and, as Newton postulated, relative to the so-called *absolute space.* In Newton's words, 'Absolute space, in its own nature, without regard to anything external, remains always similar and immovable'. Absolute space was for Newton the limitless stage on which the cosmic drama was taking place; neither influencing nor being in any way influenced by the presence and movement of the stars. Furthermore this space was assumed to be a three-dimensional Euclidean space; that is, all those theorems in Euclidean geometry we learn at school are valid in it. To summarize, Newton assumed that out of the myriad of inertial systems there was *one* inertial system, which we shall call the *absolute system*, which was at rest in this hypothetical absolute space. It was, in a sense, the search for this absolute system that led Newton's theory to its downfall.

Another assumption underlying the whole of Newtonian dynamics is the concept of an *absolute time*. Again, in Newton's words, this time 'flows equably and absolutely and without any reference to any object whatsoever'. This means, in particular, that the time-interval between any two events is the same in whichever reference system it is measured.

Very simple mathematics, indeed the very definition of inertial systems, imply that the *form* of Newton's laws of motion is exactly the same in all inertial systems. That is, as far as dynamics is concerned, all inertial frames are completely equivalent. This dynamical equivalence of all inertial systems constitutes the *classical principle of relativity*. In practical terms this means, as is well-known, that if one is in a train which is travelling on straight smooth rails at whatever constant speed, one can drink one's coffee, or read, or do one's knitting just as comfortably as when the train is at rest. The consequence of the classical principle of relativity is that Newton's absolute space becomes completely meaningless, for the principle ensures that it is impossible to locate the absolute system by any dynamical experiments.

The question naturally arises whether we can locate this absolute system by some other non-dynamical experiments. Alongside the Newtonian theory of dynamics, there was another fundamental theory which, during the latter half of the last century, was evolving rapidly with tremendous experimental support. The theory was beautifully formulated mathematically by Clark Maxwell. This formulation predicted the existence of electromagnetic waves and the electromagnetic origin of light. These predictions were later fully verified experimentally. Electromagnetic theory seemed to require a medium—called the ether—in which the energy-carrying electromagnetic (and light) waves were propagated; much in the same way as sound waves require a medium (for example, air) to propagate. But it was known, for example, that light from the sun and the distant stars travels vast distances through *empty* space before reaching the earth. Yet wave propagation without a medium was so unthinkable at the time, that the concept of ether was introduced, even though there was not even the slightest experimental evidence for its existence. Towards the end of the last century, and for some time even after the emergence of the special theory of relativity, the most widely accepted model of the ether was the so-called *luminiferous ether*. This ether was thought of as a stagnant medium, filling all space and permeating all matter. It was, furthermore, identified with Newton's absolute space.

In contradistinction to Newton's theory of dynamics, the electromagnetic theory did not satisfy the *classical* principle of relativity. In other words, Maxwell's equations describing the electromagnetic field have different form in different inertial systems. This was a great lack of *unity* in physics. For there is hardly any experiment which is purely dynamical or purely electromagnetical; and if the (classical) principle of relativity is valid in dynamics but not in electromagnetism then it becomes a principle whose meaning is, to say the least, dubious. In any case, the fact that Maxwell's equations do not have the same form in all inertial systems led Maxwell, and his contemporaries, to the belief that his equations (in their simplest form) were valid only in *one* inertial system, namely, the system which is at rest in the luminiferous ether. If this were the case then this *one* inertial system could be identified with the absolute system we referred to earlier, and hence with Newton's absolute space.

The experimental search for the absolute system was on. The most accurate, and historically the most important, experiment was carried out by Michelson and Morley in 1887. The original purpose of the experiment was to determine the velocity of the earth through the ether. Using the measurements of this experiment it should be possible, on the basis of Newtonian dynamics, to calculate the velocity of the earth with extreme accuracy. But the velocity of the earth, through the ether, thus calculated turned out to be zero. This was a stunning result. For it meant only one of two things. Either the earth was at rest relative to the ether and, therefore, the earth itself was the long-sought absolute reference system, or the ether hypothesis and Newtonian dynamics were wrong. The first alternative we can rule out on other experimental evidences and, also, on philosophical grounds. The foundations of

Newtonian theory were beginning to shake. The shattering results of the Michelson and Morley experiment, and of other experiments besides, created for physics a Gordian knot. Many ingenious attempts were made and new hypotheses were introduced to undo the knot and save the existing theories. But these hypotheses were nothing but *ad hoc* assumptions, completely extraneous to the theories concerned. The Gordian knot had to be *cut*, and it was the sharp intellect of Albert Einstein which cut it in 1905.

In his third paper of that year Einstein introduced the following two postulates:

1. The laws of nature are the same in all inertial reference systems.
2. The speed of light in vacuum is a constant, the same in all inertial reference systems.

The speed of light referred to in the second postulate is generally denoted by the letter c and it has the colossal value $c = 186{,}000$ miles (or 300,000 kilometers) per second. The above two postulates constitute the special theory of relativity (the theory is called *special* because it contemplates only reference systems in uniform translatory motion relative to each other and not systems in general relative motion). Postulate 1 is called the principle (of the special theory) of relativity. We note that it generalizes the *classical* principle of relativity to incorporate not only dynamics but *all* physical theories. The second postulate is called the principle of the constancy of the speed of light. It is the *simplest*, though by no means the only, *inference* drawn from the Michelson and Morley experiment referred to earlier (this inference was subsequently to be substantiated most convincingly by numerous experiments).

The postulates of the special theory of relativity spring from experimental evidences. If we accept them, and to accept them we must, then we must accept everything else that follows from them by logical deduction, however strange that which follows may be. Individually these two postulates seem innocent enough. But taken together they lead to fantasy and wild contradictions, if that is we retain the Newtonian concepts of space and time. We can show, for example, that a sphere has two or more different centres, or that $1 = 0$, $2 = 0$, and so on. The three key concepts that enter in each of these contradictions are *distance* (or space), *time* and *simultaneity*. The only possibility of removing these contradictions lay in the re-examination of these basic concepts. At a time when everybody considered the meaning of these concepts as self-evident Einstein set out to do just that. The results were shattering. Take *simultaneity*, that is the concept as to whether two events taking place at different points are simultaneous or not. Simultaneity is not an *a priori* concept. It must be given an operational definition, that is, it must be defined in such a way that it can be tested by measurement. This Einstein did, showing at the same time that simultaneity is not an *absolute* but a *relative* concept; if two events are simultaneous in one inertial (reference) system they are not simultaneous in any other inertial system. The realization that simultaneity is not an absolute concept must be considered as one of the greatest achievements of Einstein. For, as he showed in the same paper, *time* measurement and *distance* (or space) measurement themselves involve the concept of simultaneity in an essential and intricate way. Hence the inescapable and far-reaching conclusion that space and time are *relative* concepts. Even more important, Einstein showed that space and time are inexplicably joined together.

The old Newtonian dynamics based, as it is, on absolute space and absolute time has no place in the new theory in which neither of these concepts has any absolute meaning. Einstein formulated a new (relativistic) dynamics whose predictions, and subsequent experimental verifications, are breathtaking indeed. The new dynamics accounts for all the phenomena that Newtonian dynamics does; indeed Newtonian dynamics is a limiting case of Einstein's dynamics in that, in physical situations in which the speeds involved are small compared with the speed of light, Einstein's theory reduces to Newton's theory. When, however, the speeds involved are comparable to the speed of light the new theory makes new and exciting predictions undreamed of in Newton's theory. We mention, rather crudely, some of these predictions:

(*a*) The length of a moving rod, for example, is shorter than that of an identical rod at rest (this is called the Fitzgerald contraction after the Trinity College physicist who introduced it, in an *ad hoc* way, to explain the results of the Michelson-Morley experiment).

(*b*) The time registered by a moving clock goes slower than the time registered by an identical clock at rest. Associated with this prediction is the so-called 'twin-paradox'. It is certainly the most controversial prediction. Its numerous experimental verifications are, however, beyond any doubt.

(*c*) The mass of a body increases with its speed.

(*d*) No material particle can be accelerated to attain the speed of light, etc.

The reader may have been wondering what happened to the elusive ether of pre-relativity physics. Einstein solved the ether mystery with a single master stroke: there is no ether. 'The introduction of the luminiferous ether', he wrote, 'will prove superfluous inasmuch as the view to be developed will not require an "absolute stationary space" provided with special properties....' The reader will also recall that Maxwell's theory of electromagnetism does not satisfy the classical principle of relativity. In the same paper, his third 1905 paper, Einstein showed that this theory satisfies the (new) relativity principle. Thus the essential unity of physics, so manifestly absent in pre-relativity physics, is restored. The success of the theory of relativity, as Reichenbach puts it, 'resides in the persuasive power of the soberest and sharpest thinking as well as in its overwhelming capacity of explaining experimental facts within the frame of one unified theory.'

The fourth paper of 1905 we mentioned earlier is essentially a continuation of the third paper. It is really a prelude to a paper written two years later, in 1907. This is the paper in which Einstein derived his now famous and well-known formula

$$E = m\,c^2 \; (c = 186{,}000 \text{ mps or } 300{,}000 \text{ km ps}).$$

That is, the energy, E, of a particle of mass m (both E and m being measured in the same inertial system) is equal to the mass of the particle multiplied by the speed of light squared. Energy and mass become, according to this equation, different manifestation of one and the same thing. Due to the large value of the factor c^2 the energy of even a small mass is tremendous. If mass can be converted to energy efficiently mankind would have for ever solved its 'energy problem'. This formula may truly prove to be Einstein's promethean gift to humanity. It is a gift, however, that man can use to improve his lot or to lead him to his annihilation. The atomic bomb whose construction was theoretically predicted by this formula is a terrifying reminder of the latter.

The story is told that the eminent physiochemist Walter Nerst (who seemed to have a love-hate relationship with Einstein) remarked in one of his lectures that if someone made a discovery as great as $E = mc^2$, he could retire there and then, resting on his laurels for the rest of his life. When this remark was reported back to Einstein, he laughed and said: 'He would love that, the old rascal, but I am not going to oblige.'

Despite its far reaching consequences Einstein's work was by no means readily recognised. He had to continue working at the Patent Office (where, on the first of April 1906, he was promoted to Technical Expert Second Class) and carrying his own research until October 1909. In that year he bid farewell to the Patent Office, 'that secular cloister where I hatched my most beautiful ideas' as he put it ten years later, to take up an Associate Professorship in the University of Zurich. Einstein was now on the road to fame. Invitations to important conferences and offers of academic posts came pouring in. He held full professorships in quick succession in the University of Prague and in the Zurich Polytechnic from which he graduated twelve years earlier. In the summer of 1913 the great scientists Plank and Nerst, whom we met before, visited Einstein personally and offered him the directorship of the newly established Institute of Physics at the Kaiser Wilhem Institute in Berlin. The Berlin of those years was probably the greatest scientific centre in the world. So despite his misgivings about German militarism Einstein was to settle in Berlin for the next eighteen years of his life. Einstein did not 'rest on his laurels'. His scientific output was as prolific as it was fundamental. He made major contributions to statistical mechanics, quantum theory and relativity. But slowly, patiently, and with unbelievable obstinacy, he was laying down the foundations of his greatest edifice, the edifice of the general theory of relativity.

As early as 1907, in the $E = mc^2$ paper, he was already speculating about gravitation and *general* relativity. The special theory of relativity had been unable to deal, in any satisfactory way, with gravitation. The fact that special relativity deals only with inertial reference systems was, to Einstein, unsatisfactory. Why should any one reference system, inertial or non-inertial, be more important than another? Although uniform motion is relative in both special relativity and Newtonian theory, non-uniform motion is not; one can drink one's coffee comfortably in a train which moves uniformly, but not if the train jerks and jolts, or goes around a bend, or if the brakes are suddenly applied. Einstein, influenced by the Viennese philosopher Mach, would not accept absolute motion of any kind. He was searching for a theory in which *all* reference systems are completely equivalent in formulating physical laws and in which the ghost of absolute motion disappears altogether. Einstein's only clue in this search lay in gravitational phenomena.

In the meantime a new development took place in 1908 which was instrumental in the formulation of the general theory of relativity. This was the *geometrization* of the special theory of relativity by the eminent mathematician Minkowski, one of Einstein's former professors at the Polytechnic. As we have seen, Einstein showed in 1905 that neither distance nor time measurements have any absolute meaning nor are space and time independent entities. This was never put more beautifully, or with deeper conviction than Minkowski in 1908: 'Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.'

Minkowski realized that the concept which is of fundamental importance is neither a point in space nor an instant in time but the *event*, something happening at a certain point at a certain time. 'Nobody has ever noticed a place except at a time, or a time except at a place', he said. Our world is the world of physical phenomena, the collection of all events. And this world is a *four-dimensional* world simply because an event in it is uniquely specified by *four*, and only four, numbers. Three of these numbers specify the *position*, relative to some inertial system, at which the event takes place, and the fourth specifies the *time*, relative to the same inertial system, at which the event takes place. We denote these numbers by (x_1, x_2, x_3, t) and call them the *coordinates* of the event relative to a specified inertial system. The event, of course, has different coordinates in different inertial systems (the special theory of relativity gives us the exact relationship between these different coordinates). Consider an event which takes place at the point P at time t and an event which takes place at the point Q at time T as measured in some inertial reference system which we call S. Thus the coordinates of the events at P and Q, in the system S, are of the form

(x_1, x_2, x_3, t) and (X_1, X_2, X_3, T), respectively. Einstein showed in 1905 that the quantity Φ, defined by

$$\Phi = (\text{distance between P and Q})^2 - c^2 (T - t)^2,$$

has the remarkable property that it is the same in *all* inertial reference systems. That is, out of the two *relative* quantities (distance between P and Q)^2 and $(T - t)^2$, we get a quantity which is *absolute*. In terms of the coordinates (x_1, x_2, x_3, t) and (X_1, X_2, X_3, T) the defining equation for Φ takes the form

$$\Phi = (X_1 - x_1)^2 + (X_2 - x_2)^2 + (X_3 - x_3)^2 - c^2 (T - t)^2 .$$

When the two events are near to each other, in space and in time, it is customary to write

$$X_1 - x_1 = dx_1 , X_2 - x_2 = dx_2 , X_3 - x_3 = dx_3 , T - t = dt ,$$

where dx_1 , dx_2 , etc., denote small numbers. Hence the above equation becomes

$$\Phi = (dx_1)^2 + (dx_2)^2 + (dx_3)^2 - c^2 (dt)^2 . \quad (1)$$

Minkowski's great achievement was the realization that this expression defines a *geometry* of the world of events. Hence space and time are now unified into a single entity called *space-time*; this space-time is 4-dimensional and has a geometry defined by the above expression. Owing to the minus sign entering in this expression this geometry differs considerably from the Euclidean geometry. But since, as can easily be shown, straight lines, in the sense of Euclid, do exist space-time is called a *flat* 4-dimensional space, just as Euclidean spaces are called.

Minkowski changed nothing of Einstein's work. But he did *reformulate* the whole of the special theory of relativity in a revealing and most elegant way using the geometrical language and the geometrical properties of the Minkowski, as it is now called, space-time. In doing so he prepared the way for Einstein's final formulation of the *general* theory of relativity. Einstein himself had this to say about Minkowski's contribution: 'Without it the general theory of relativity, . . . , would perhaps have got no further than its long clothes.'

The general theory of relativity is, above all, a theory of gravitation. It was, as was mentioned earlier, by an intricate analysis of gravitational phenomena that Einstein found the clue for the development of his theory. In particular, the analysis of what has long been known as the law of *Galileo:* if two bodies are released from the same height they will reach the ground at the same instant, irrespective of the constitution of the bodies (air resistance is assumed to be absent). In short, in the absence of air resistance, *all bodies fall equally fast* in a gravitational field. Einstein realized that this important universal law is the consequence of the fundamental experimental result that, to an incredible degree of accuracy, the *inertial* mass of a body is equal to the *gravitational* mass of the body. The inertial mass of a body is a measure of the *inertia* of the body, i.e., the ability of the body to resist acceleration. The gravitational mass of a body is a measure of the ability of the body to produce, or to be influenced by, a gravitational field.

Using the equality of the inertial and gravitational mass, or equivalently Galileo's law, Einstein was able to arrive at his so-called *principle of equivalence.* 'In a small region of space-time inertia and gravitation are indistinguishable.' This implies that in this small region gravitation can be got rid of. The reader may think of this region as a spacecraft circling the earth with its engines turned off—the astronauts, as well as their papers and pencils when let free, float around as if there is no gravity. A reference system attached to this small region, the spacecraft, behaves like an inertial reference system (locally). Einstein assumed that in this small region the special theory of relativity is valid, i.e., the geometry in this region is the Minkowski geometry described by the expression

$$\Phi = (dx_1)^2 + (dx_2)^2 + (dx_3)^2 - c^2\,(dt)^2\,.$$

Accordingly, Einstein argued, in the presence of gravitation we must look for a *generalization* of the Minkowski geometry—a generalized geometry which can be reduced, over a small region of space-time, to the Minkowski geometry. (The insistence on a *small region* is crucial, for if the geometry were to reduce to the Minkowski geometry *throughout* space-time this would imply the *complete* absence of gravitation.)

The answer to this problem was known to the pure mathematicians some fifty years before Einstein's theory. The only such geometry is the 4-dimensional *Riemannian* geometry. It is described by the expression

$$\begin{aligned}\Phi = g_{11}\,(dx_1)^2 + g_{12}\,(dx_1)\,(dx_2) + g_{13}\,(dx_1)\,(dx_3) + g_{14}\,(dx_1)\,(dx_4)\\ + g_{22}\,(dx_2)^2 + g_{23}\,(dx_2)\,(dx_3) + g_{24}\,(dx_2)\,(dx_4)\\ + g_{33}\,(dx_3)^2 + g_{34}\,(dx_3)\,(dx_4)\\ + g_{44}\,(dx_4)^2. \qquad (2)\end{aligned}$$

Three of the coordinates (x_1, x_2, x_3, x_4) of an event, say the first three, are the spacial coordinates and the last one, x_4 , the time coordinate of the event. These coordinates are much more general than those used in the Minkowskian expression (1). Indeed they are quite arbitrary and without any *a priori* physical meaning. The ten quantities g_{11}, g_{12}, etc., depend on the coordinates (x_1, x_2, x_3, x_4) and, therefore, the expression Φ changes from event to event. These quantities describe fully the geometrical structure of space-time (of general relativity). Since, according to this geometry there are no straight lines, in the sense of Euclid, this space-time is called *curved* or *warped*. Obviously we can have an infinity of Riemannian spaces simply by changing the dependence of the quantities g_{11}, g_{12}, etc., on the coordinates (x_1, x_2, x_3, x_4). Hence there still exists the problem of how to *determine* these ten quantities which will describe the geometry of the actual universe or of a specific physical system. By mathematical skill, and deep physical insight of the highest grade, Einstein discovered a set of equations—known as Einstein's field equations—which determine the values of these quantities. The outcome was his general theory of relativity, a work of such stupendous originality, and with such profound consequences, as to make it unparalleled in the entire history of the human mind.

We have mentioned earlier that the quantities g_{11}, g_{12}, . . . , fully describe the geometrical structure of space-time. Now, according to Einstein's field equations, the values of these quantities depend directly on the distribution and motion of matter. Hence the *geometry* of space-time depends directly on the distribution and motion of matter—a far cry from Newton's absolute space. Furthermore the ten quantities g_{11}, g_{12}, . . . , take the place of the single Newtonian gravitational potential (the quantity which describes the gravitational field). Thus in Einstein's theory gravitation is a geometrical property of space-time; it is no longer a force as in Newton's theory. If special relativity unified space and time, general relativity unified space, time, matter and gravitation in a *geometrical* grand design. Surprising that Einstein, unlike Plato two and a half thousand years earlier, never said 'God always geometrizes'.

The general theory of relativity is of extreme mathematical beauty and logical simplicity. It is, of course, a mathematically difficult theory, but as Einstein said 'God does not care about our mathematical difficulties'. But it is also a *physical* theory and, as such, the supreme arbiter for its acceptance or rejection is experiment and observation. How did the theory withstand the test of experiment? The answer must be: 'triumphantly', for the following reasons:

1. All the experimental verifications of Newton's theory, and there are many, are verifications of Einstein's theory as well. For weak gravitational fields and for speeds which are small compared with the speed of light Newton's theory is a special case of Einstein's theory.
2. *Advance of the perihelion.* Just as Newton's theory predicts that the orbit of a planet around its sun is an ellipse, so does Einstein's theory. But, whereas in Newton's theory the orbit is stationary (i.e. it does not change position), in Einstein's theory the ellipse is slowly rotating around the sun in the direction of the motion of the planet (fig. 1). In the case of the orbit of the planet Mercury it has been known since 1859

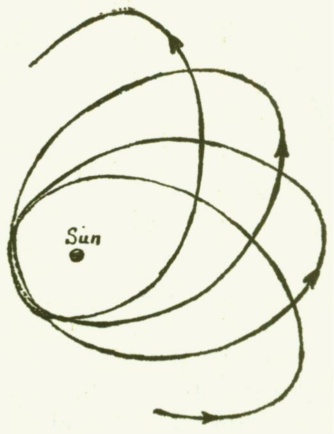

FIG. 1.

that the orbit (ellipse) makes a complete revolution around the sun every 3,000,000 years. General relativity predicts exactly this value. This phenomenon is known as 'the advance of the perihelion'.

3. *Deflection of light.* The theory predicted an entirely new phenomenon, namely, the path of a light ray in a gravitational field is not a straight line. The theory predicted, for example, that a light ray from a distant star crazing the surface of the sun is deflected through an angle of 1·75 seconds of arc (fig. 2).

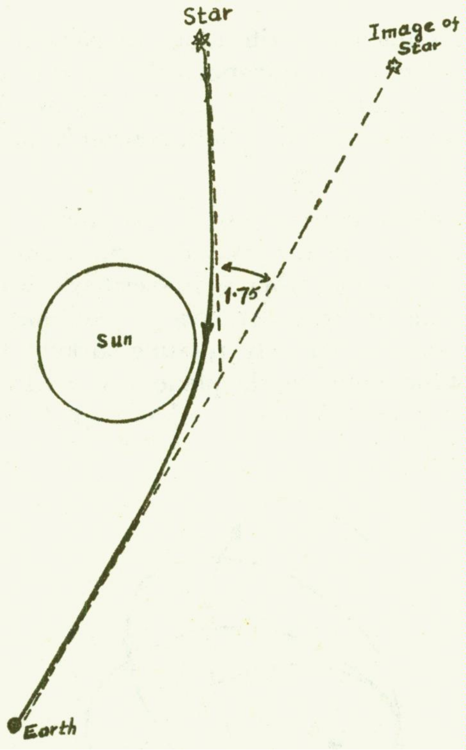

FIG. 2.

This prediction was verified during the total eclipse of the sun, on 29 May 1919, in an atmosphere of unimaginable excitement and suspense. The Royal Society and the Royal Astronomical Society of England organised two expeditions, one to Sobral (in Brazil) and the other to Principe (a small island off the West coast of Africa). Sir Arthur Eddington[1] was put in charge and he, together with the astronomer, Cottingham, headed the Principe party. The night before sailing Eddington, Cottingham and the Astronomer Royal, Sir Frank Dyson, were in Dyson's study discussing the amount of the light deflection predicted by Einstein. Cottingham asked, 'What will it mean if we get double the Einstein deflection?'. To which the Astronomer Royal replied, 'Then Eddington will go mad and you will have to come back alone'. Three months later, when Eddington made some rough calculations from the photographic plates of the eclipse he turned to Cottingham and said, 'Cottingham, you won't have to go home alone'. Eddington remarked later that that moment was one of the happiest moments of his life. His overflowing happiness found expression in poetry as one of his verses (a parody of Omar Khyam) indicates:

Oh leave the Wise our measures to collate,
One thing at least is certain, light has weight,
One thing is certain, and the rest debate,
Light rays, when near the sun, DO NOT GO STRAIGHT.

The observational results of both expeditions, as well as of numerous subsequent observations, were in full agreement with Einstein's prediction. When Einstein was asked what would have happened if the observations did not agree with his prediction, his reply was, 'Then I would have felt sorry for the Good Lord'.

4. *Gravitational red-shift.* The last of the 1916 predictions of general relativity concerns, essentially, the influence of a gravitational field on time. According to the theory any rhythmic process, a clock or a vibrating atom for example, becomes slower as the gravitational field becomes stronger. This prediction was, again, in full agreement with observation.

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[1] Eddington was the greatest apostle of general relativity. It was he who spread the 'gospel according to Einstein' to the English-speaking world. Around 1916, in the early days of general relativity, he was reputed as one of the very few theoretical physicists who understood the theory. The story goes that around that time a physicist remarked to Eddington, 'You are one of three men who understand relativity theory'. When a pained expression appeared on Eddington's face, the physicist said, 'Professor Eddington, you shouldn't be embarrassed; you are too modest'. Eddington replied, 'No, I am not embarrassed; I am only wondering who is the third man'.

> Subsequent predictions of the theory withstood the test of experiment and observation just as successfully.

The year 1919, in which the bending of light was verified, is a landmark in Einstein's life. His fame spread throughout the world overnight. He became a folk hero, a demigod. He was befriended and entertained by royalties and Emperors and Presidents. The public adulation he was to receive from now on could only be compared with that given to royalties and the best of the screen stars. It was a fame that Einstein never craved for and which, indeed, became a nuisance to him. 'I envy the simplest working man. He has his privacy', he once said to one of his collaborators. And on another occasion he remarked: 'I appear to myself as a swindler because of the great publicity about me without any real reason'. He had his photograph taken so many times that he once said 'I am like a prima donna'. Another time when a reporter asked him what his job was Einstein replied: 'A model'.

In 1919 Einstein got married to his widowed cousin Elsa. This marriage gave him the warmth and comfort which were essential for his work. The year 1919 marked the beginning of antisemitism in Germany. An Anti-Einstein league was formed offering large sums of money to anyone who would write papers 'refuting his theories'. Public lectures were held in the huge concert halls of Berlin denouncing relativity. (Some lectures were also held in support of Einstein's theory. Einstein himself was persuaded once to give a public lecture and Leopold Infeld, who in later years was to collaborate closely with Einstein, recalls how, during the lecture, Einstein played with a stick that was on the table. One lady asked another, 'why doesn't he leave the stick alone?' But, says Infeld, she soon saw the point. 'When Einstein showed by gestures how a stick moves and contracts, the relieved lady whispered to her neighbour, "I did not know that this is the contracting stick".') With Hitler's rise to power, Einstein left Berlin in 1932. The following year he went to the Princeton Institute for Advance Study where he was to spend the rest of his life.

In the meantime Einstein continued making major contributions to quantum theory and general relativity. Shortly after 1916 he applied his general theory of relativity to the universe as a whole. It was from this work that cosmology emerged from the realm of myth and science fiction to become the exciting scientific inquiry that it is today. The study of gravitational waves started at about the same time and the problem of the equations of motion a few years afterward. Both these topics still dominate present-day research in relativity. But as early as 1922 Einstein's extraordinary urge and desire to generalize and synthesize lead him to an entirely new and exciting idea. A grand synthesis in which space, time, matter, gravitation *and* electromagnetism would all be unified. This, the loftiest of his ideas, was the 'unified field theory'; it was to occupy his life to the very end. But, although Einstein came up with a number of truly ingenious formulations (some of which appeared in newspapers throughout the world with sensational headlines), the idea was never fully materialized. For, unlike the development of the general theory of relativity in which he had one physical clue, namely the equality of the inertial and gravitational mass, in his search for a 'unified field theory' Einstein had no physical clue whatsoever. His only guidance, if such it can be called, was his belief in the essential unity of physics. Because of the successes of the (geometric) theory of relativity he also believed that such a 'unified field theory', too, must be geometrical. It must also be pointed out that in his search for a 'unified field theory' Einstein was almost completely alone. Quantum theory was becoming the centre of interest. Einstein, who did so much to create it, now turned his back to it. He refused to accept the *probabilistic* interpretation given to the theory in 1924 by M. Born and L. Heisenberg. In a letter to Born in 1926 Einstein wrote: 'Quantum Mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing. The theory says a lot, but does not really bring us any closer to the secret of the "old one". I, at any rate, am convinced that He is not playing at dice.'

We have indicated earlier that Einstein's world-wide fame meant very little to him. As a man he retained his simplicity, his kindness, and his passionate concern for humanity. During his stay at Princeton he lived in a modest house within walking distance from the Institute. He spent his winters working either at home or at the Institute, and he spent his summers (in a rented summer cottage near the village of Peconic on Long Island) sailing, playing chamber music and working. He used his authority to help many Germans, friends and former colleagues and even strangers, to escape the Nazi persecution. He was always ready to write letters of recommendation for job-hunting physicists. Infeld, the Polish Jew physicist who himself received immensurable help from Einstein, wrote: 'He wrote so many letters of recommendation that his generosity became known, and the letters were kept as valuable autographs rather than letters of recommendation. I heard a true story concerning an opening in a hospital for an X-ray physicist, for which several refugees applied. Each had a recommendation from Einstein.' But of all the letters to which Einstein put his signature, by far the most important and best known was the one written on 2 August 1939, and addressed to Roosevelt, the President of the United States. It is said, but only with slight and qualified justification, that this is the letter that opened the gate to the 'atomic age'. We have mentioned earlier that the construction of the atomic bomb was theoretically embodied in Einstein's formula $E = mc^2$ of 1907. At that time, and for many years afterwards, any practical applicability of this formula, let alone the construction of a bomb, was considered by Einstein and other physicists quite remote. But this was to change dramatically in the 1930s. With the advances in nuclear physics during this period, and especially the splitting of the uranium atom in 1939, the theoretical possibility of the atomic bomb was turned into a practical certainty. When Hitler occupied Czechoslovakia in the spring of 1939 he immediately took over the rich uranium mines and stopped the export of uranium. To many physicists (prominent among them Szilard, Wigner and Teller from Hungary, and Fermi from Italy, and all refugees) this was a sure indication that Germany was trying to build the bomb. With growing alarm as to what might happen if Germany acquired the bomb first Fermi tried, unsuccessfully, to alert the United States Navy. Szilard (who, incidentally, was the first to realise quite clearly the construction of nuclear reactors and the bomb in 1934) and his compatriot Teller approached Einstein for his help. Einstein helped with the first draft of the aforementioned letter to Roosevelt. The final version, modified and translated into English by Szilard, was approved and signed by Einstein on 2 August 1939. The letter initiated the Manhattan Project and the eventual construction of the bomb. On hearing of the explosion of the bomb over Hiroshima on 6 August 1945 Einstein could only utter the words, 'Oh, weh!' ('Oh! woe!'). From that moment onward he threw himself unsparingly into the cause of saving mankind from a nuclear holocaust. The very last public act of his life was the signing of Russell's statement, later known as the Russell-Einstein statement, on the nuclear arms race.

Einstein must have been a wonderful man to know, to hear and to see. While in Princeton he acquired the image of the 'absentminded professor'. He never went to the barber and wore his hair long and unkempt. He wore baggy trousers with no suspenders (with the result that, while explaining something on the blackboard, he had to pull up his trousers every few seconds). He wore no collar, no ties and no socks (because his toes would only make holes in them!). He loved to tell, and listened to, jokes and would laugh loudly at them, especially at his own jokes. This is how the late Professor Lanczos (of the Dublin Institute for Advanced Studies, and a life-long friend of Einstein) described Einstein's laughter: 'His laugh was completely unburdened; it came from the depths, starting with a small rivulet and then burst in a gradual crescendo to a mighty explosion of uninhibited mirth.' Many jokes and aphorisms are attributed to Einstein. We mention two of them. To make the point that gravitational force, though by far the weakest force we know, is a very important force he told the joke: 'An unmarried woman had a child and the family was greatly humiliated. So the mid-wife tried to console the mother by saying: "Don't worry so much, it is a very small child" '. And, 'I am something of a Jewish saint. When I die, the Jews will take my bones to a banquet and collect money'. The Jews did consider Einstein as something of a Jewish saint. In 1952 they offered him the highest possible honour of becoming Israel's President. He declined with the utmost humility.

Einstein died on 18 April 1955, on the fiftieth birthday of his special theory of relativity. Beside his bed lay the pages of an unfinished calculation on the unified field theory. This last act of his life aptly epitomizes Einstein's total dedication to his scientific work. The last *public* act of his life, the signing of the Russell statement, aptly epitomizes Einstein's passionate concern for humanity.

Relativity to-day is as alive and exciting as never before. It inspires the latest research in astrophysics, black holes, gravitational waves, cosmology, and so on. What of the future of the theory of relativity? Despite what Lagrange said, that 'the science of our world can be created only once', history has told us that the science of our world is *not* created only *once*. Science is a dynamic, ever evolving process. Scientific theories are created to explain physical phenomena (and to predict new ones). In the light of new discoveries, or more exact experimental and observational results, unaccounted by, or inconsistent with, the relevant theory, the theory is abandoned or, perhaps more correctly, generalized to account for the old as well as the new results. Whatever the fate of the theory of relativity may be this much can be said with absolute certainty. The concept of absolute simultaneity, absolute space, and absolute time will forever remain buried. The theory of relativity will stand as the greatest achievement of the human intellect throughout the ages. A fitting monument to the extraordinary genius of its creator, Albert Einstein.

This article was first given as a public lecture in Trinity College on 26 April 1979 to mark the centenary of Einstein's birth (14 March 1879).