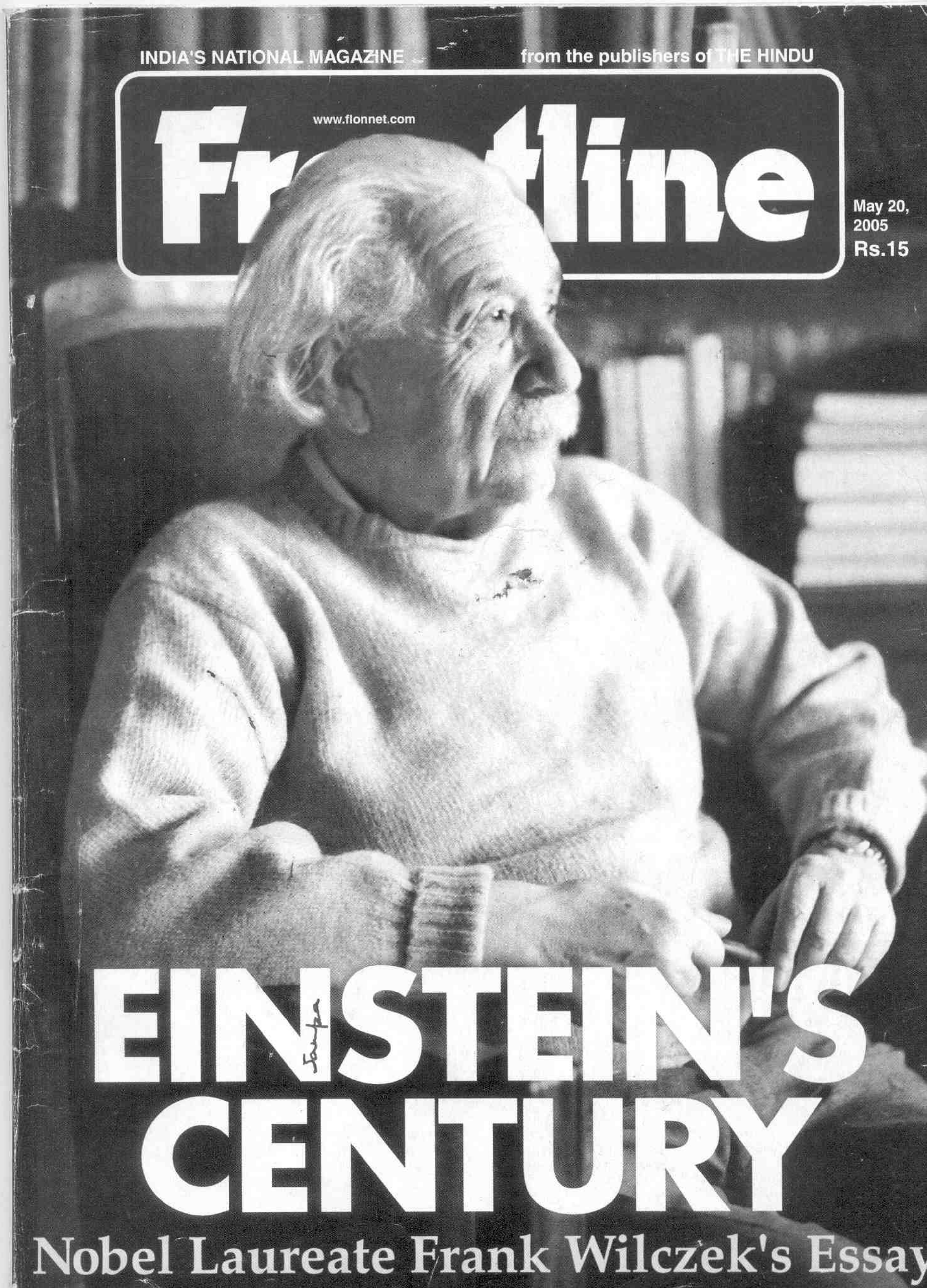

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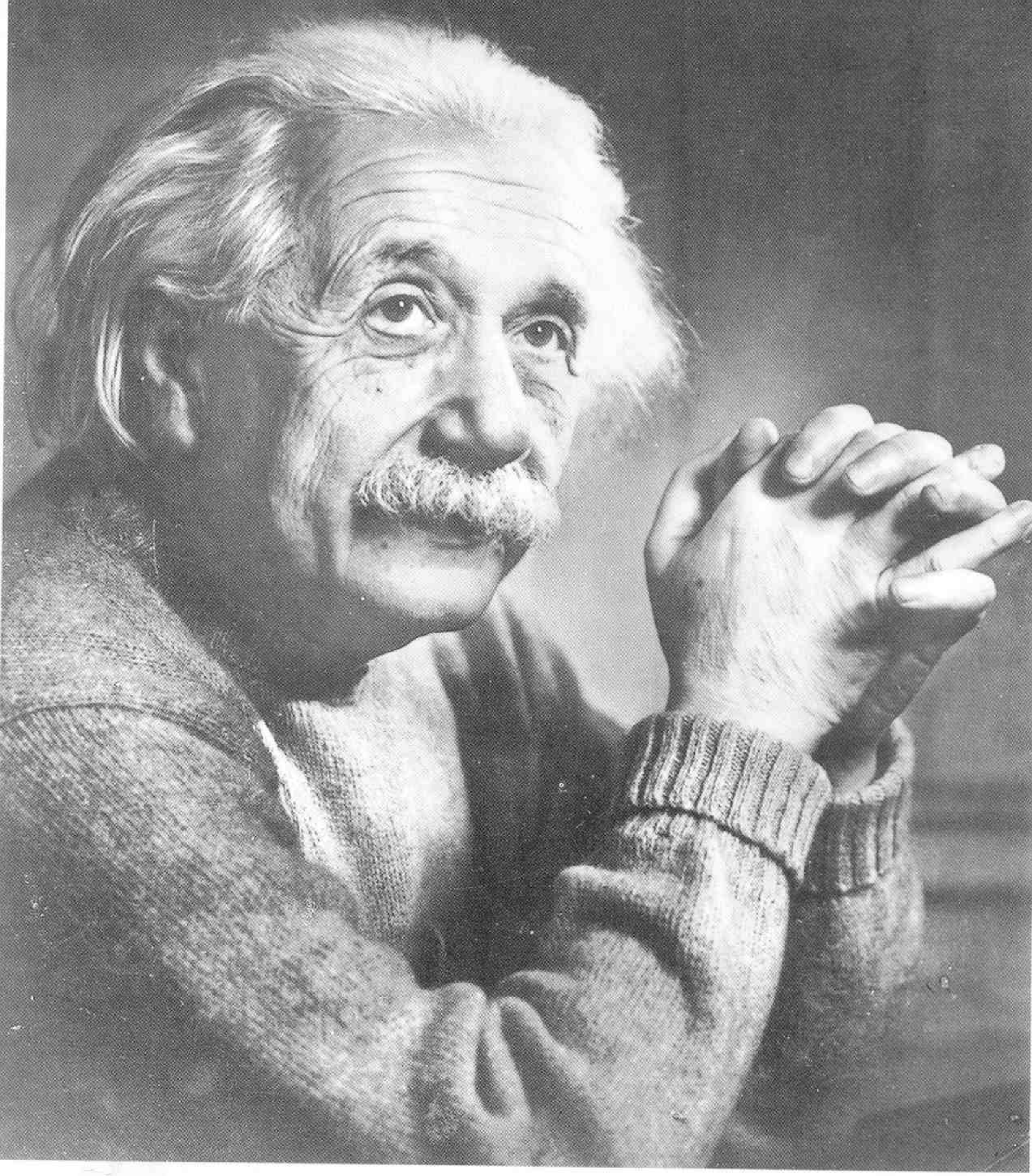
EINSTEIN'S CENTURY

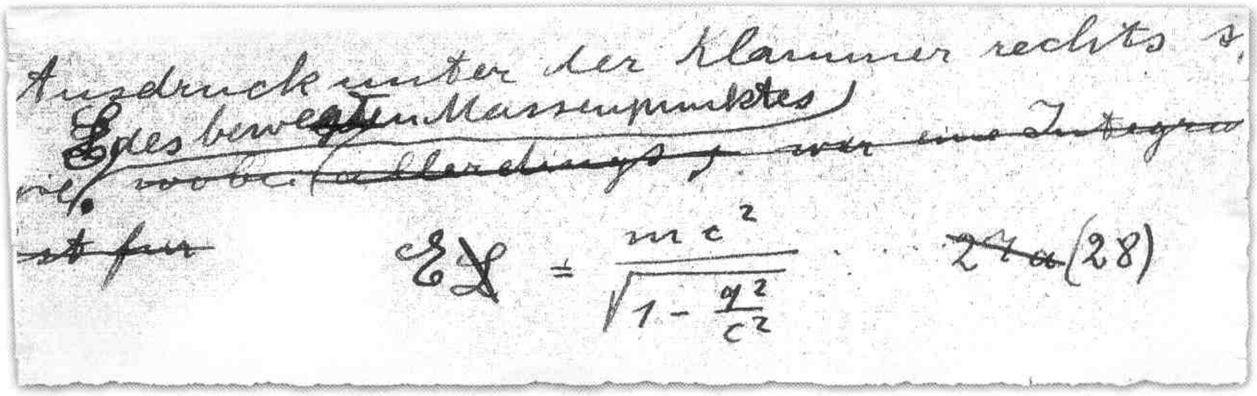
Nobel Laureate Frank Wilczek's Essay

COVER STORY

EINSTEIN'S CENTURY

In the World Year of Physics 2005, a hundred years after Albert Einstein initiated a revolutionary turn away from classical physics with four seminal papers, a celebration of the scientist-philosopher's legacy.





SOTHEBY'S/AP

Einstein's famous equation $E = mc^2$ in a manuscript written by the physicist in 1912. The autographed 72-page working manuscript was the earliest in which Einstein outlined his Theory of Relativity.

T. JAYARAMAN

IN the spring of 1905, a hundred years ago, a young man began the journey from obscurity to scientific stardom. Within a decade, the young Albert Einstein would be hailed as a genius who towered over his contemporaries, even in an era that had no dearth of brilliant minds in science. Soon the comparisons would begin to transcend his century, and he would take his place alongside Isaac Newton and Charles Darwin.

In that magical year, the 26-year-old Einstein, without a formal academic position and sustained by employment in the Swiss Federal Patent Office, was to publish four epochal papers within the space of seven months in the German journal *Annalen der Physik*, one of the pre-eminent scientific journals of his time. In these four papers, Einstein would initiate a revolutionary turn away from classical physics, abandoning some of its most cherished assumptions. The seemingly effortless ease and rapidity with which this was accomplished and the sheer magnitude of what resulted thereby appears even today, in the age of rapid scientific advance, breathtaking.

Physics would no longer be the same after 1905. The comforting link between mundane sensory experience and the fundamental laws of nature that had existed in Newtonian physics even after the Copernican revolution would now be lost forever. With Einstein began the age when, as he himself was to emphasise, the fundamental concepts of science would be "farther removed from the sphere of immediate experience, if we aim at a profounder understanding of relationships".

A century after the work that placed Einstein firmly in the ranks of the greatest names in the history of science, His legacy is ubiquitous in science and his fundamental contributions very much a part of the standard lore of physics. Paradoxically though, physics has advanced so far down the road that he first took, and the frontiers of his discipline have extended so far beyond where they were in his day, that we are perhaps in danger of missing the extraordinary transformations that Einstein effected in our fundamental understanding of nature.

What did Einstein accomplish in those four papers of 1905?

Chinese physicists wave as an image of Einstein is projected during a laser show in Shanghai on April 19. The event was part of a worldwide relay of lights to commemorate the World Year of Physics and Einstein's 50th death anniversary.

Three days after his 26th birthday, on March 17, Einstein completed the first of this remarkable series. Received by the journal on March 18, and published on June 9, the paper was titled "On a heuristic point of view concerning the generation and conversion of light". This paper was the first shot in the quantum revolution. In this paper Einstein framed, unambiguously, the hypothesis that light in its interaction with matter behaves like a particle with a discrete amount or 'quantum' of energy proportional to its frequency. Over the next two decades the hypothesis was to be verified experimentally, leading to his Nobel Prize for physics in 1921.

The second paper, received by the journal on May 11 and published in the issue of July 18, concerned itself with the explanation of Brownian motion, the phenomenon of random motion executed by particles suspended in a fluid. The work was an immediate outgrowth of his doctoral thesis, which itself was completed only a few days earlier, on April 30, and submitted to the University of Zurich. This paper, as Einstein cheerfully noted in a letter to a friend, once and for all settled the question of the reality of atoms. It also developed methods that lie at the root of modern statistical physics, particularly in the study of systems out of equilibrium.

Some time in mid-May, Einstein had that definite moment of discovery that opened the road to the formulation of the Special Theory of Relativity. The result was the third paper, received by *Annalen der Physik* on June 30 and published on September 26, titled "On the electrodynamics of moving bodies". It abolished the notion that electromagnetic radiation required some kind of medium, the 'ether' as it was known, for its transmission. Indeed, the problem of the 'ether' had occupied the young Einstein for almost a decade and was the subject of a precocious essay that he sent to his uncle, Cesar Kock, in Belgium in 1895. Einstein also postulated that the velocity of light was always constant, independent of the velocity of the emitter.

In the resulting unification of space and time, Einstein advanced decisively beyond Newtonian mechanics, a process that he was to complete with the General Theory of Relativity in 1915. The mathematician Hermann Minkowski, one of the few teachers from his university days that Einstein respected, noted in an influential review of the Theory of Relativity in 1908: "The views of space and time which I wish to lay before you have sprung from the soil of experimental physics and therein lies their strength. They are radical. 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" (as quoted in the pre-eminent scientific biography of Einstein, *'Subtle is the Lord…': The Science and Life of Albert Einstein*, by Abraham Pais, Clarendon Press, Oxford, 1982).

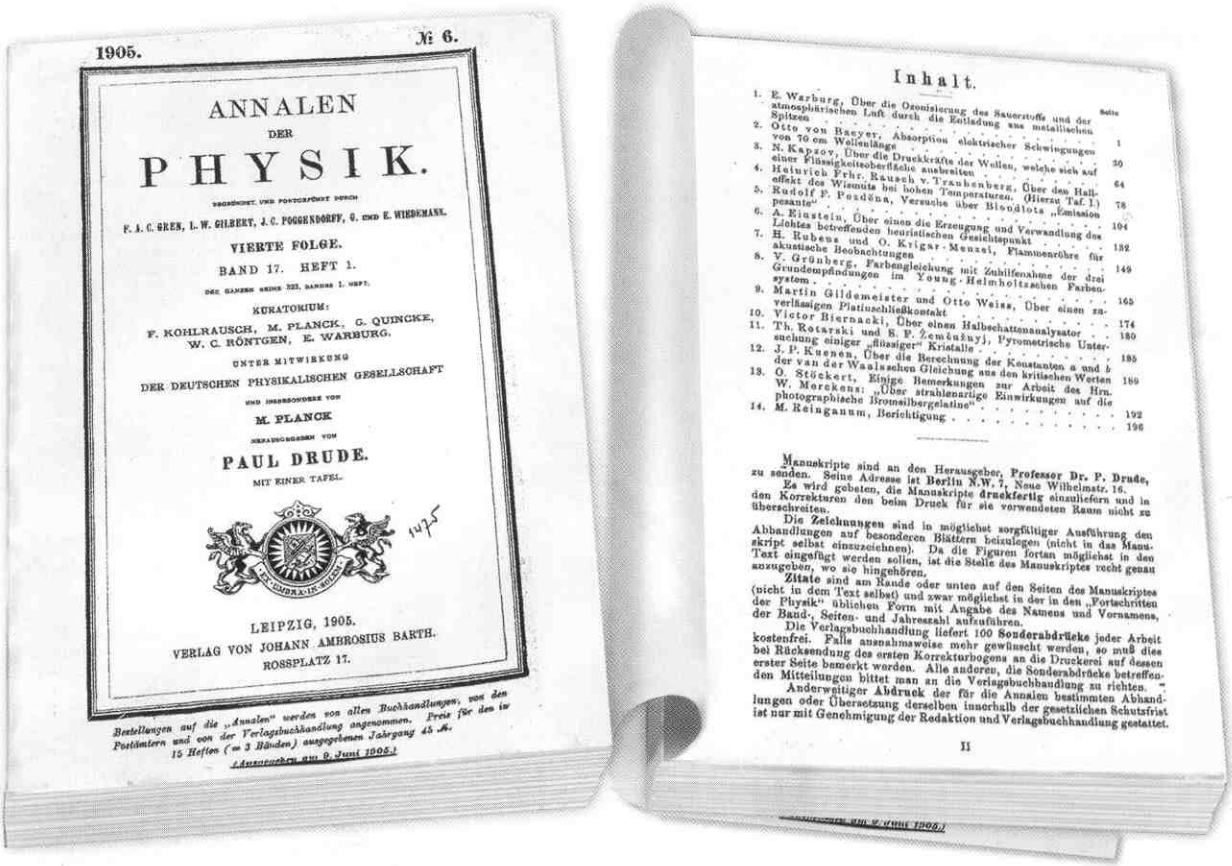
In the fourth paper, received by the journal on September 27 and published on November 21, Einstein announced the result that energy is proportional to mass, as a consequence of the Special Theory of Relativity. The constant of proportionality is the square of the speed of light. By then, on July 27, Einstein's doctoral thesis had been accepted, and he sent it for publication to *Annalen der Physik,* which received it on August 19. It was published only the next year after some additions made at the request of the editors.

Within months of the publication of these four papers of 1905, Einstein had arrived in the academic world of his time. By 1906, he was in correspondence with leading physicists of his day like Max Planck, who was to describe Einstein some years later, while recommending him for a professorship, as a 'modern Copernicus'. Contrary to some variants of the popular myth, Einstein's work of that year found rapid acceptance in the world of science. Three years later Einstein was to leave the patent office to enter the academic world, but the legend of the unknown patent clerk, the lonely genius, who effected a complete revolution in science was born.

Einstein, in 1905, was not unaware of the scientific currents of his time, particularly in relation to the questions that were uppermost in his mind. There were also significant gaps, leading occasionally to the rediscovery of known results. In later years, he was to reflect profoundly on the history and philosophical and scientific antecedents of the problems he addressed in the papers of 1905. But in that extraordinary year, Einstein was to leap forward with brilliant simplicity beyond the science of his day.

There was one more brilliant success that awaited Albert Einstein, the second phase of his radical departure from classical physics. In 1915, he finally succeeded in extending the Theory of Relativity to matter in acceleration, resulting in a new theory of gravitation, where mass was identified as the curvature of space-time. But this was hard won success, and the final work was built on a succession of earlier papers, some of them in collaboration with Marcel Grossman, his friend from his university days. The confirmation of this theory came from the solar eclipse expedition of 1919, data from which observed the bending of light from

The title page of the first issue of Volume 17 of *Annalen der Physik*, published on June 9, 1905. The table of contents at right lists Einstein's paper on the light quantum hypothesis.



1905. № 6.

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Inhalt.

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II

Early influences

T. JAYARAMAN

ALBERT EINSTEIN, the first child of Hermann Einstein and Pauline Koch, was born at Ulm, in Germany, on March 14, 1879. According to most biographers, Einstein was a quiet child who stayed apart from his classmates, and was not much inclined to sports or gymnastics, which made him "dizzy and tired". He was given to occasional fits of temper, though. On one occasion, as a five-year old, he threw a chair at a teacher who taught him at home.

Einstein did not have a particularly remarkable school or university record, though he always performed well in mathematics and the sciences. Einstein was distinctly unhappy with the school he attended from age 9 to 15, the Luitpold Gymnasium in Munich, and disliked the authoritarian teachers, servile students and rote learning that he had to endure there. When his father moved the family to Italy, leaving Einstein behind to finish school in Munich, the young Albert, pleading illness, managed to leave his school and rejoin his family in Italy.

Outside the regular curriculum, though, Einstein was always deeply interested in science. In "Autobiographical Notes", which he wrote for the volume *Albert Einstein: Philosopher-Scientist,* he notes the deep sense of wonder he experienced as a child of five when his father showed him a compass. He was struck by the idea that "something deeply hidden had to be behind things". The next major influence he records in the notes is his reading a book on Euclidean plane geometry at the age of 12, whose "lucidity and certainty made an indescribable impression upon me". His father's brother Jakob introduced him to algebra. When he was 12, a family friend, Max Talmud, introduced Einstein to several works on science and philosophy. Among the many books he gave the young Albert was *The Critique of Pure Reason* by Immanuel Kant. It was a book that Einstein took to easily and thus began a life-long interest in philosophy. Talmud was to recall later in an introductory book on the Theory of Relativity that the young Einstein's mathematical talents were enormous and that he soon outran Talmud's own knowledge.

After leaving Munich, Einstein's first attempt to enter the Federal Institute of Technology (or ETH in its German acronym) at Zurich in Switzerland ended in failure owing to his poor performance in subjects other than mathematics and the sciences. He subsequently entered the ETH in October 1896, after he passed the Swiss high school diploma examination, the Matura. Einstein detested the university examination system, which, as he described it in "Autobiographical Notes" almost 50 years later, forced him to "cram all this stuff, whether one liked it or not".

He regarded himself fortunate that he had to appear for only two examinations during his entire stay in the University, which enabled him to study what he pleased except for a few months before the examination. Einstein thought his teachers of mathematics were good, but it was physics that attracted him, even though he had a poor opinion of the physics faculty. Einstein paid particular attention to the study of electromagnetism, which was not part of the regular curriculum. He also studied the work of Ernst Mach and was to be heavily influenced by his critique of Newtonian mechanics, though not by his philosophy. Towards the end of his university days he was studying closely the current state of "ether physics", a subject that reflected the confusion in the classical physics of that time.

In contrast to his school years, Einstein forged lasting friendships while studying in Zurich, including the one with his fellow student Marcel Grossman. Einstein graduated in August 1900. Three other students who graduated with him received assistantships at the ETH, but Einstein was denied one. One of the professors of physics, Weber, who was always critical of Einstein's independence and whom Einstein had grown to dislike intensely, refused to give him a seat after having promised it.

There was one last disappointment in his academic career that awaited Einstein. He took up appointments as a temporary teacher in schools, the first in May 1901 and the second in September 1901. Einstein enjoyed the freedom to work on whatever physics problems struck his fancy after his teaching hours were over. But the University of Zurich rejected his doctoral thesis on the kinetic theory of gases, which he submitted in late 1901. The thesis work itself though was published later.

Einstein obtained his appointment at the Swiss Federal Patent Office in Berne in July 1902, after responding to an advertisement for a position there. Earlier, Marcel Grossman's father had recommended Einstein's name to the head of the patent office for a job. He began his patent office career as a technical expert, third class, and was promoted to technical expert, second class, in April, 1906. In 1909, he left the patent office to begin his academic career. ■

the stars by the sun, which had been predicted by Einstein's new theory of gravity.

Subsequently, Einstein's scientific journey was to become more complex and difficult. He never reconciled himself to the eventual form that quantum mechanics took in the hands of Werner Heisenberg, Paul Dirac, Erwin Schrodinger and Max Born, under the influence of Niels Bohr.

While he was gradually convinced that quantum mechanics was not inconsistent, he nevertheless believed that it was incomplete. Einstein liked even less the application of the methods of quantum mechanics to electromagnetic fields. The man who initiated the quantum revolution remained unhappy with what became of it in the hands of its Jacobins.

Thus began an isolation from the mainstream that was to intensify in his years at the Institute of Advanced Study at Princeton in the United States, where he settled after leaving Nazi Germany in 1933. His attempts in his Princeton years to formulate a unified theory of gravitation and electromagnetism did not make much progress and was considered a fruitless project by many of his contemporar ies. Twentieth-century science pushe forward far more relentlessly than the sc ence of the 17th or even the 19th centur and the manner in which scientific deve opments outran Einstein in his later yea was not a fate that befell a Newton or Maxwell in their lifetime.

But Einstein's larger vision undoub edly set the agenda, if only in part, f subsequent developments that cam much later. The search for a unified the ry of all fundamental forces has now b come an integral part of the paradigm fundamental physics. And in partial vindication of Einstein, the integration of quantum mechanics and the General Theory of Relativity on the basis of some fundamental principles remains a challenge despite evidence of some progress in recent decades.

After the spectacular affirmation of Einstein's theory of gravity by the solar eclipse expedition of 1919, a world wearied by the First World War greeted Einstein as a new popular hero. There was intense interest worldwide in Einstein and his work. In India, it resulted in the publication of the first-ever English translation of the papers of Einstein and Minkowski by Satyendranath Bose and Meghnad Saha, with a foreword by P.C. Mahalanobis (photograph on page 23).

Even prior to his rise to fame, Einstein had begun to step out into the world of public affairs, signing a manifesto against German militarism in 1917. Einstein was to be a pacifist all his life, except for the period that the Nazis were in power, and was drawn naturally to the ideals of Gandhi. Though he signed the letter urging the U.S. President to develop the atomic bomb, he was horrified by its use. He was unwaveringly opposed to nuclear weapons and it was a cause that occupied him till the end of his days.

Einstein was one of the few intellectuals in the U.S. to speak up against the anti-communist witch-hunts of the McCarthy era. In 1949, he wrote a short note titled "Why Socialism?" for the inaugural issue of the communist journal *Monthly Review*, an act of considerable courage at a time when the U.S. was slipping into a phase of intolerance and anti-communist hysteria. For several years the Federal Bureau of Investigation (FBI) kept him under surveillance. Einstein, though, remained an undaunted champion of civil liberties.

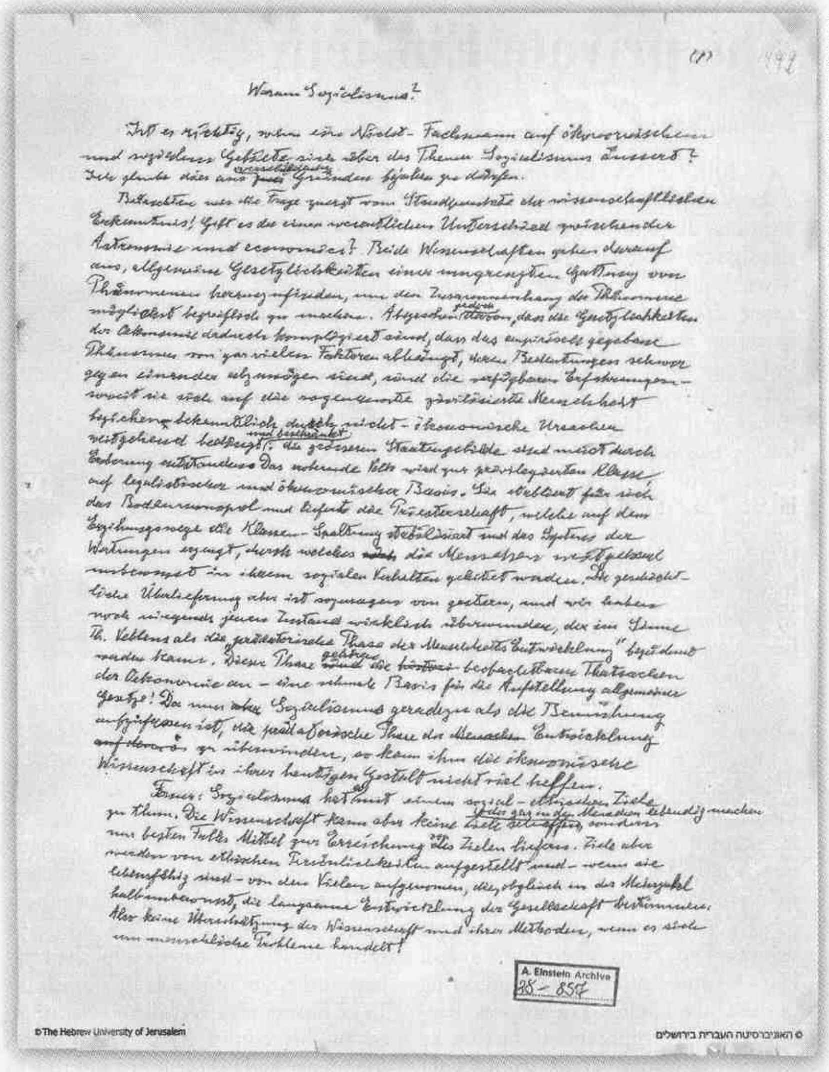
Einstein, born in an irreligious Jewish family, had no great attraction for religion through most of his life. But he was a firm supporter first of Zionism and then the state of Israel and lent his name to several other Jewish causes through the years. Shocked by the Holocaust, which claimed the lives of several of his relatives including two cousins, he shunned all contact with Germany, the land of his birth, except for a few close friends.

What was the origin of Einstein's willingness to support causes that went against the mainstream and were certainly unpopular with those in positions of power? Perhaps it was an extension of his scientific spirit to the realm of human affairs, as Niels Bohr noted in his obituary comments on Einstein: "The gifts of Einstein are in no way confined to the sphere of science. Indeed, his recognition of hitherto unheeded assumptions in even our most elementary and accustomed assumptions means to all people a new encouragement in tracing and combating the deep-rooted prejudices and complacencies inherent in every national culture" (as quoted in *Einstein Lived Here*, by Abraham Pais, Clarendon Press, Oxford, 1994).

No scientist before him and few after him so entrenched themselves in the public consciousness as Albert Einstein did. He was a public icon, recognised by people across the world, in an era before television brought the world to everyone's door. The formula that will always be associated with his name is perhaps the one scientific equation that is easily recognised by anyone. Half a century after his death, his image even today is perhaps more familiar than that of most contemporary men and women of science.

In his lifetime, he acquired a moral stature that compelled the attention, albeit reluctant, of governments and political leaders when he spoke up on issues, which were not lacking in the first half of a century marked by social and political turmoil. From philosophy to the arts, intellectual life was not complete without engaging with his ideas and work.

Yet to Einstein himself, despite his considerable involvement in matters other than science, especially in his later years, his scientific work was always to be at the core of his being, the very definition of his persona. Nowhere is this clearer than in the substance and style of his "Autobiographical Notes" that he wrote for the vol-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Warum Sozialismus?

Ist es richtig, wenn ein Nicht-Fachmann auf ökonomischen und sozialen Gebieten sich über das Thema Sozialismus äussert? Ich glaube dies aus verschiedenen Gründen bejahen zu dürfen.

A. Einstein Archive
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COURTESY: THE HEBREW UNIVERSITY OF JERUSALEM

In 1949, Einstein wrote a short note titled "Why Socialism?" in German, which was translated into English and published in the inaugural issue of *Monthly Review.* Above is a reproduction of the first page from the draft of the note.

The private Einstein

T. JAYARAMAN

ALBERT EINSTEIN once wrote to an old friend of his ETH days: "I am so far all right in that I have victoriously survived the Nazi time and two wives" (quoted by A. Pais in *Einstein Lived Here*). On another occasion, speaking ostensibly about his pipe-smoking habit, Einstein remarked: "My aim lies in smoking, but as a result things tend to clog up, I'm afraid. Life too is like smoking, especially marriage." Einstein's private life was complicated and difficult, marked by many ups and downs, though he made other lasting personal friendships, particularly with his scientific colleagues or those with whom he had shared intellectual interests.

CHRISTIE'S NEW YORK/AP

A 1910 photo of Einstein and his first wife Mileva Maric, taken in Prague.

Einstein's first wife was Mileva Maric, a fellow student at the ETH, whom he married in 1903 after overcoming his family's objections. At that time they had a two-year-old daughter, Lieserl, who was given for adoption, a fact known to biographers only in the early 1980s. Subsequent efforts by Einstein scholars to trace her whereabouts proved unsuccessful. Albert and Mileva had two sons, Hans Albert and Eduard. Hans became a professor of engineering in the United States. Eduard was diagnosed with schizophrenia at the time he entered university. Hans would later comment with some bitterness that he was the one project that his illustrious father gave up on.

Einstein and Mileva separated, with much harshness on Einstein's part and bitterness on hers, in 1914, with the children being in the custody of Mileva. The claim in some quarters that Mileva contributed substantially to the development of the Special Theory of Relativity, and was perhaps an unacknowledged second author, has been rejected decisively by Einstein scholars and biographers.

Einstein struggled with the General Theory of Relativity, achieving success in November 1915. In an extraordinary burst of activity from then until the spring of 1917, Einstein published papers at the rate of one every month. In 1917 Einstein fell very ill and was nursed by his cousin Elsa. Their correspondence had begun after a meeting in 1912 and the correspondence had grown increasingly affectionate and later intimate.

Einstein married Elsa in 1919 after a divorce settlement with Mileva, which included the payment of Einstein's Nobel Prize money to her when it was won. Einstein's relationship with Elsa was not one of great intimacy. Einstein, though, seems to have always had numerous affairs through the years, a bohemian streak he himself, very indirectly, acknowledged. Current Einstein biographies tend to the view that his private persona was much less lovable than his public image would suggest.

Elsa died in 1936 after the Einsteins moved to the U.S. Einstein was joined by his beloved sister Maria (Maja) in 1939 in the U.S. Einstein was always close to her and he attended on her in her last days in Princeton in 1951.

For more than 20 years, Helen Dukas was Einstein's secretary. Increasingly, she managed Einstein's household and took care of him till the end. She was named as one of the two trustees of Einstein's estate in his will in 1950, a task that she carried out until her death in 1982. ■

ume *Albert Einstein: Philosopher-Scientist* edited by P.A. Schlipp (published by The Library of Living Philosophers Inc., Evanston, Illinois, USA, 1949). The note, which Einstein begins by describing it as "my own obituary", has no reference even to the bare facts of his life, apart from brief comments on his education and the intellectual influences of his childhood and youth. It is entirely devoted to a short account of his main work and the philosophical and scientific questions that led up to them.

He interrupts a critique of Newtonian physics in the note to remark: "'Is this supposed to be an obituary?' the astonished reader will likely ask. I would like to reply: essentially yes. For the essential in the being of a man of my type lies precisely in what he thinks and how he thinks, not in what he does or suffers."

Einstein continued to work at his desk on his scientific problems until the end of his life. Again contrary to myth, Einstein in the academic milieu was very much a professional scientist. His scientific writings number more than 300, a large output even by contemporary standards. In his last days at Princeton, he continued to be held in awe by his scientific colleagues, even if they did not follow what he said (as Einstein was to complain to his friend Johanna Fantova, a University of Princeton librarian), as he worked and lectured amongst them. He lived quietly, walking every day between his office at the Institute of Advanced Study and his home, where he was ministered to by his faithful secretary Helen Dukas. To the men, women and children of that little town, the grandfatherly figure was a gentle and benevolent presence.

Einstein died on April 19, 1955, at the age of 75, after a brief stay in hospital following a ruptured aneurysm. ■

T. Jayaraman is a theoretical physicist at the Institute of Mathematical Sciences, Chennai.

■ COVER STORY

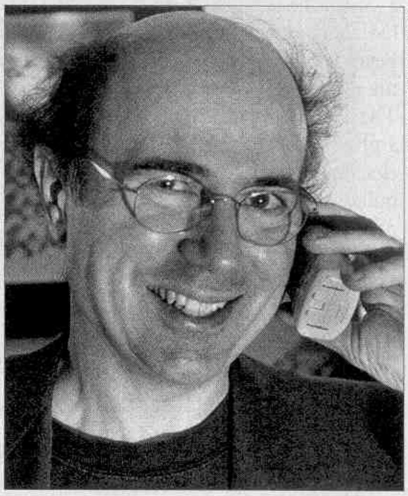
THE ORIGIN OF MASS

In this World Year of Physics Essay written for *Frontline*, the Nobel Prize-winning physicist explains how his own work on subnuclear forces casts new light on the origin of mass from energy.

Professor Frank Wilczek is considered one of the world's most eminent theoretical physicists. He is known, among other things, for the discovery of asymptotic freedom, the development of quantum chromodynamics, the invention of axions, and the discovery and exploitation of new forms of quantum statistics (anyons).

When only 21 years old and a graduate student at Princeton University, in work with David Gross he defined the properties of colour gluons, which hold atomic nuclei together. He was jointly awarded the Nobel Prize for Physics in 2004, together with Prof. David Gross and Prof. H.D. Politzer, for the discovery of asymptotic freedom.

Professor Wilczek taught at Princeton from 1974 to 1981. Subsequently he held distinguished chairs in physics at the University of California at Santa Barbara and the Institute for


BRIAN SNYDER/REUTERS

Advanced Study, Princeton. In 2000, he moved to the Massachusetts Institute of Technology, where he is currently the Herman Feshbach Professor of Physics.

Professor Wilczek has been a Sloan Foundation Fellow (1975-77) and a MacArthur Foundation Fellow (1982-87). Apart from the Nobel Prize, he has received numerous awards for his contributions to the development of theoretical physics.

He is a member of the National Academy of Sciences in the United States, the Netherlands Academy of Sciences and the American Academy of Arts and Sciences, and is a Trustee of the University of Chicago.

Prof. Wilczek is an award-winning communicator of science and contributes regularly to *Physics Today* and to *Nature*, explaining topics at the frontiers of physics to wider scientific audiences.

Two of his pieces have been anthologised in *Best American Science Writing* (2003, 2005). Together with his wife Betsy Devine, he has written a book, *Longing for the Harmonies* (W.W. Norton). ■

FRANK WILCZEK

EVERYDAY work on the frontiers of modern physics usually involves complex concepts and extreme conditions. We speak of quantum fields, entanglement, or supersymmetry, and analyse the ridiculously small or conceptualise the incomprehensibly large. Just as Willie Sutton famously explained that he robbed banks because "that's where the money is", so we do these things because "that's where the Unknown is". It is an amazing and delightful fact, however, that occasionally this sophisticated work gives answers to childlike questions about familiar things. Here I would like to describe how my own work on subnuclear forces, the world of quarks and gluons, casts brilliant new light on one such childlike question: What is the origin of mass?

This is an especially appropriate topic for the World Year of Physics 2005, because it relates so closely to the circle of ideas around Albert Einstein's most famous equation, $E = mc^2$. That equation,

written in that form, immediately suggests the possibility of converting small quantities of mass into large quantities of energy – a suggestion that was realised, of course, with the development of nuclear reactors and nuclear weapons. It is worth noting, however, that this is not the way the equation appears in Einstein's original paper. In that paper you do not find $E = mc^2$, but rather $m = E/c^2$. The difference is trivial algebraically, but profound conceptually, for the second (original) form of the equation suggests something quite different: the possibility to derive mass from energy. For a modern physicist, and even for Einstein in 1905, this sounds a deeper resonance. Energy appears a pervasive, primary concept in modern physics, and there is no real prospect of explaining it in terms of something more basic. For mass the situation is quite different. The title of Einstein's paper is "Does the Inertia of a Body Depend Upon Its Energy Content?". It shows that from the beginning, Einstein was thinking about questioning the foundations of fundamental physics, not making bombs. Modern physics, as I shall now explain, answers his question with a resounding "Yes!"

Has mass an origin?

That a question makes grammatical sense does not guarantee that it is answerable, or even coherent. The concept of mass is one of the first things we discuss in my freshman mechanics class. Classical mechanics is, literally, unthinkable without it. Newton's Second Law of Motion says that the acceleration of a body is given by dividing the force acting upon it by its mass. So a body without mass would not know how to move, because you would be dividing by zero. Also, in Newton's Law of Gravity, the mass of an object governs the strength of the force it exerts. One cannot build up an object that gravitates, out of material that does not, so you cannot get rid of mass without getting rid of gravity.

Finally, the most basic feature of mass in classical mechanics is that it is conserved. For example, when you bring together two bodies, the total mass is just the sum of the individual masses. This assumption is so deeply ingrained that it was not even explicitly formulated as a law. (Though I teach it as Newton's Zeroth Law.) Altogether, in the Newtonian framework it is difficult to imagine what would constitute an "origin of mass", or even what this phrase could possibly mean. In that framework mass just is what it is – a primary concept.

Later developments in physics make the concept of mass seem less irreducible. Einstein's famous equation for the interconvertibility of mass and energy, already mentioned, was the watershed. In modern particle accelerators, this possibility comes to life. For example, in the Large Electron Positron collider (LEP), at the CERN laboratory near Geneva, beams of electrons and antielectrons (positrons) were accelerated to enormous energies. Powerful, specially designed magnets controlled the paths of the particles, and caused them to circulate in opposite directions around a big storage ring. The paths of these beams intersected at a few interaction regions, where collisions could occur. When a collision between a high-energy electron and a high-energy positron occurs, we often observe that many particles emerge from the event. The total mass of these particles can be thousands of times the mass of the original electron and positron. Thus mass has been created, physically, from energy.

Having convinced ourselves that the question of the origin of mass might make sense, let us now come to grips with it, in the concrete form that it takes for ordinary matter. Ordinary matter is made from atoms. The mass of atoms is overwhelmingly concentrated in their nuclei. The surrounding electrons are of course crucial for discussing how atoms interact with each other – and thus for chemistry, biology, and electronics. But they provide less than a part in a thousand of the mass! Nuclei, which provide the lion's share of mass, are assembled from protons and neutrons. All this is a familiar, well-established story, dating back to 70 years or more. Newer and perhaps less familiar, but by now no less well-established, is the next step: protons and neutrons are made from quarks and gluons. So most of the mass of matter can be traced, ultimately, back to quarks and gluons.

QCD: What it is

The theory of quarks and gluons is called quantum chromodynamics, or QCD. QCD is a generalisation of quantum electrodynamics (QED). For a nice description of quantum electrodynamics, I highly recommend "QED: The Strange Theory of Electrons and Light", written by a Massachusetts Institute of Technology (MIT) graduate who made good, Richard Feynman. The basic concept of QED is the response of photons to electric charge. The elementary act in QED is emission of a photon by a charged particle. From this elementary act, the whole theory can be built up deductively, using the powerful rules of special relativity and quantum mechanics. The rules for electric and magnetic forces, from atomic to cosmic scales, and for radiation and absorption of light and radio waves – what the great physicist Paul Dirac called "all of chemistry and most of physics" – all emerge by deduction from the elementary act.

It is like making constructions with TinkerToys. The particles are different kinds of sticks you can use, and the elementary act provides the hubs that join them. Given these elements, the rules for construction are completely determined. In this way all the content of Maxwell's equations for radio waves and light, Schrodinger's equation for atoms and chemistry, and Dirac's more refined version including spin – all this, and more, are faithfully encoded in QED.

At this most primitive level QCD is a lot like QED, but bigger. The diagrams look similar, and the rules for evaluating them are similar, but there are more kinds of sticks and hubs. More precisely, while there is just one kind of charge in QED – namely, electric charge – QCD has three different kinds of charge. They are called colours, for no good reason. We could label them red, green and blue. Every quark has one unit of one of the colour charges. In addition, quarks come in different species, or "flavours". The only two that play a role in ordinary matter are two flavours called u and d, for up and down. (Of course, quark "flavours" have nothing to do with how anything tastes. And, these names for u and d do not imply that there is any real connection between flavours and directions. Don't blame me; when I get the chance, I give particles dignified scientific-sounding names like axion and anyon.)

There are u quarks with a unit of red charge, d quarks with a unit of green charge, and so forth, for six different p bilities altogether. And instead of one ton that responds to electric charge, C has eight colour gluons that can eithe spond to different colour charges or ch one into another. So there is quite a variety of sticks, and there are also n different kinds of hubs that connect th With all these possibilities, it seems things could get terribly complicated messy. And so they would, were it no the overwhelming symmetry of the the If you interchange red with blue ev where, for example, you must still get same rules. The more complete symm allows you to mix the colours continu ly, forming blends, and the rules n come out the same for blends as for p colours.

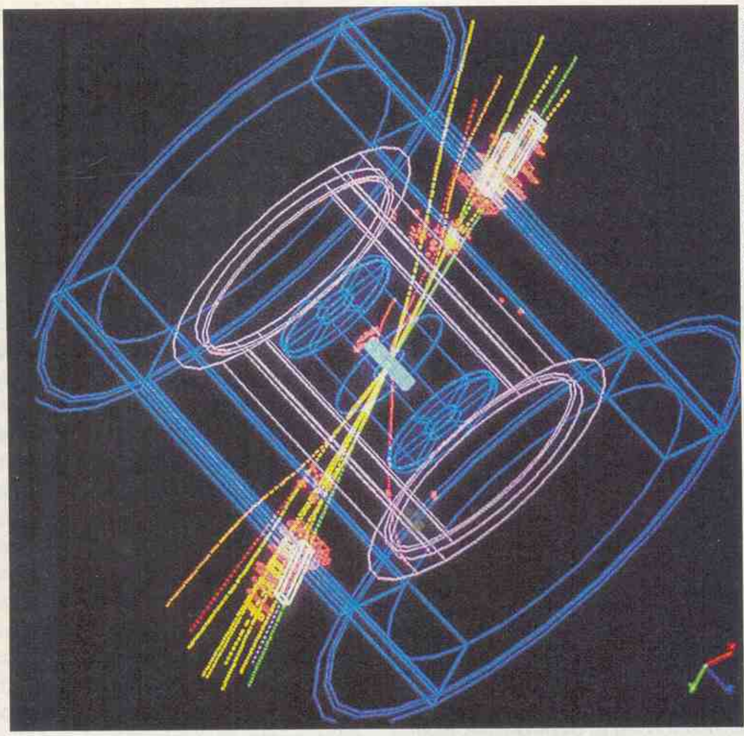
I shall not be able to do justice to mathematics here, of course. But the fi result is noteworthy and easy to conv there is one and only one way to ass rules to all the possible hubs so that theory comes out fully symmetric. Intric it may be, but messy it is not! With th understandings, QCD is faithfully enc ed in a single elementary act and its sy metric cousins. We thereby arrive definite rules, realised as precise equatio which predict how quarks and gluons b have and interact. Solving the equatic can be very difficult, but if they are solve there is no ambiguity about the outcon The theory is either right or wrong – the is nowhere to hide.

How we know QCD is right

Experiment is the ultimate arbiter scientific truth. There are many exper ments that test the basic principles QCD. Most of them require rather sophi ticated analysis, basically because we do no get to see the underlying simple stuff, th individual quarks and gluons, directly. Bu there is one kind of experiment that come very close to doing this, and that is what would like to explain now.

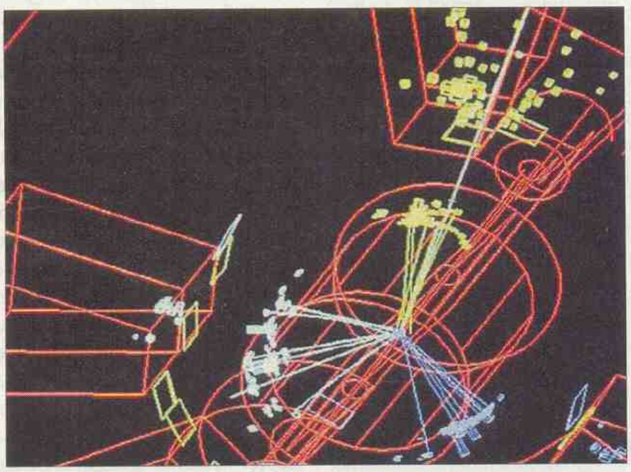
I shall be discussing what was observe at LEP. Before entering into details, would like to highlight a fundamenta point about quantum mechanics, which i necessary background for making an sense at all of what happens. According to the principles of quantum mechanics, the result of an individual collision is unpredictable. We can, and do, control the energies and spins of the electrons and positrons precisely, so that precisely the same kind of collision occurs repeatedly.

Nevertheless, different results emerge. By making many repetitions, we can determine the probabilities for different outcomes. These probabilities encode basic



CERN PHOTO COURTESY: DELPHI COLLABORATION

A two-jet event: The tracks of particles emerging from this high-energy collision at the Large Electron Positron collider (LEP) at the CERN laboratory near Geneva mark the directions set by an underlying quark and antiquark.



CERN PHOTO COURTESY: L3 COLLABORATION

A three-jet event: The tracks of particles emerging from this high-energy collision at the LEP mark the directions set by a quark, an antiquark, and a gluon. The probability that a given jet pattern emerges depends on the relative angles between the jets and the total energies they carry in an intricate manner. QCD, the fundamental theory of these particles, allows us to predict this dependence precisely.

information about the underlying fundamental interactions; according to quantum mechanics, they contain all the meaningful information.

When we examine the results of collisions at LEP, we find there are two broad classes of outcomes. Each happens about half the time.

In one class, the final state consists of a particle and its antiparticle moving rapidly in opposite directions. These could be an electron and an antielectron, a muon and an antimuon, or a tau and an antitau. The electron, muon and tau have one unit of negative electric charge, while their antiparticles have one unit of positive electric charge. These particles, collectively called leptons, are all closely similar in their properties.

Leptons do not carry colour charges, so their main interactions are with photons, and thus their behaviour should be governed by the rules of QED.

This is reflected, first of all, in the simplicity of their final states. Once produced, any of these particles could – in the language of elementary acts – attach a photon using a QED hub, or alternatively, in physical terms, radiate a photon. The basic coupling of photons to a unit charge is fairly weak, however. Therefore each additional attachment is predicted to decrease the probability of the process being described, and so the most usual case is no attachment. In fact the final state that includes a photon does occur, with about 1 per cent of the rate of the particles simply scattering off each other (and similarly for the other leptons). By studying the details of these 3-particle events, such as the probability for the photon to be emitted in different directions (the "antenna pattern") and with different energy, we can check all aspects of our hypothesis for the elementary act. This provides a wonderfully direct and incisive way to check the soundness of the basic conceptual building block from which we construct QED. We can then go on to address the extremely rare cases (.01 per cent) where two photons get radiated, and so forth. For future reference, let us call this first class of outcomes "QED events".

The other broad class of outcomes contains an entirely different class of particles, and is in many ways far more complicated. In these events the final state typically contains ten or more particles, selected from a menu of pions, rho mesons, protons and antiprotons, and many more. These are all particles that in other circumstances interact strongly with one another, and they are all constructed from quarks and gluons. Here, they make a smorgasbord of the Greek and Latin alphabet. It is such a mess that physicists have pretty much given up on trying to describe all the possibilities and their probabilities in detail.

Fortunately, however, some simple patterns emerge if we change our focus from the individual particles to the overall flow of energy and momentum.

Most of the time – in about 90 per cent of the cases – the particles emerge all moving in either one of two possible directions, opposite to one another. We say there are back-to-back jets. (Here, for once, the scientific jargon is both vivid and appropriate.) About 9 per cent of the time, we find flows in three directions; about .9

per cent of the time, four directions; and by then we are left with a very small remainder of complicated events that are hard to analyse this way. I shall call the second broad class of outcomes "QCD events".

Now if you squint a little, you will find that the QED events and the QCD events begin to look quite similar. Indeed, the pattern of energy flow is qualitatively the same in both cases, that is, heavily concentrated in a few narrow jets. There are two main differences. One, relatively trivial, is that multiple jets are more common in QCD than in QED. The other is much more profound. It is that, of course, in the QED events the jets are just single particles, while in the QCD events the jets are sprays of several particles.

In 1973, while I was working as a graduate student with David Gross at Princeton University, I discovered the explanation of these phenomena. The key was a theoretical discovery I shall describe momentarily, which we christened asymptotic freedom. Actually, our discovery of asymptotic freedom preceded these specific experiments. We were inspired by much less direct evidence. As things actually happened, therefore, we were able to predict the properties of these jets, which exhibit the fundamentals with ideal simplicity, before they were observed.

The basic concept of asymptotic freedom is that the probability for a fast-moving quark or gluon to radiate away some of its energy in the form of other quarks and gluons depends on whether this radiation is "hard" or "soft". Hard radiation is radiation that involves a substantial deflection of the particle doing the radiating, while soft radiation is radiation that does not cause such a deflection. Thus hard radiation changes the flow of energy and momentum, while soft radiation merely distributes it among additional particles, all moving together. Asymptotic freedom says that hard radiation is rare, but soft radiation is common.

This distinction explains why on the one hand there are jets, and on the other hand why the jets are not single particles. A QCD event begins as the materialisation of quark and antiquark, similar to how a QED event begins as the materialisation of lepton-antilepton. They usually give us two jets, aligned along the original directions of the quark and the antiquark, because only hard radiation can change the overall flow of energy and momentum significantly, and asymptotic freedom tells us hard radiation is rare. When a hard radiation does occur, roughly 10 per cent of the time at

LEP, we have an extra jet! But we do not see the original quarks, antiquarks, or gluons individually because they are always accompanied by their soft radiation, which is common.

By studying the antenna patterns of the multi-jet QCD events we can check all aspects of our hypotheses for the underlying hubs. Just as for QED, such antenna patterns provide a wonderfully direct and incisive way to check the soundness of the elementary acts from which we construct QCD.

Through the analyses of this and many other applications, physicists have acquired complete confidence in the fundamen correctness of QCD. By now experime ters use it routinely to design experimei searching for new phenomena. I have liv to see the same activity which used to called "testing QCD" become described "calculating backgrounds"!

The origin of mass, by calculation

Following the flow of energy and m mentum in violent collisions allows us check the fundamental ideas of the theor but using that theory to calculate the mas es of proton and other strongly interactir particles presents additional challenge The difficulty is with the soft radiatioi which we cannot ignore in this contex Since such radiation is emitted very easil it is difficult to keep track of it all. To mee that challenge, a radically different strateg is required. Instead of calculating the path of individual quarks and gluons throug space and time, we let each segment c space-time keep track of how many quark and gluons it contains. We then treat thes segments as an assembly of interactin subsystems.

Actually in this context "we" means collection of hard-working CPUs of a larg number of powerful computers. Skilfully orchestrated, and working at teraflop speeds for months at a time, they manage to calculate the properties of the protons and other strongly interacting particles that emerge as the possible stable arrangements of quarks and gluons – including, of course, their masses. The calculated masses agree quite accurately with the observed ones. In my opinion, this accurate calculation of the origin of masses, starting with a tight fundamental theory embodying profound physical concepts and mathematical symmetry, is one of the greatest scientific achievements ever. So that is the origin of (most) the mass of the proton and other strongly interacting particles.

With the answer in hand, let us interpret what we have got. For our purposes it is instructive to compare two versions of QCD, an idealised version I call QCD Lite, and the realistic Full-Bodied version. QCD Lite is cooked up from massless gluons, massless u and d quarks, and nothing else. (Now you can fully appreciate the wit of the name.) If we use this idealisation as the basis for our calculation, we get the proton mass low by about 5 per cent. Realistic, Full-Bodied QCD differs from QCD Lite in two ways. First, it contains four additional flavours of quarks. These do not appear directly in the proton, but they do have some effect on the calculation. Second, it allows for non-zero masses of the u and d quarks. The realistic value of these

The WYP logo

TO brand the World Year of Physics (WYP) and to market the various physics outreach and promotional activities that have been planned worldwide as part of the celebration, a colourful logo has been created. Designed by Paul Stearn of the European Physical Society (EPS), it has the shape of an hourglass (sand clock) to depict the passage of time as time is intrinsic to all science and especially to physics.

In the context of the centenary of 1905, when Einstein dramatically altered our notion of time, the design can also be seen to represent the light cone in the Special Theory of Relativity. The vertical refers to the time dimension and the horizontal the spatial dimension, and the intersection of the diagonals represents 'here and now' – the origin. The crossing diagonal lines represent the paths, or 'world lines', of the light signal. Since nothing can travel faster than light, the cones represent the universe that is causally connected to the present through information carried by light signals. The cone below represents the past and the one above, the future.

Of course, the design can have many other creative interpretations as well: just the colours of light, focal length, the inverse-square law, refraction of light through a lens, warped space-time or a wormhole (of time travel) in Einstein's theory of gravitation (general relativity).

At the base is written 'U.N. International Year of Physics', acknowledging the U.N. General Assembly Resolution on the WYP. ■

masses, though, turns out to be small, just a few per cent of the proton mass. Together these corrections change the predicted mass of the proton by about 5 per cent, as we pass from QCD Lite to Full-Bodied QCD. So we find that 95 per cent of the proton (and neutron) mass, and therefore 95 per cent of the mass of ordinary matter, emerges from an idealised theory whose ingredients are entirely massless.

Understanding the calculation

Now I have shown you the theory that describes quarks and gluons and therefore has to account for most of the mass of matter. I have described some of the experiments that validate theory. The calculations of particle masses employ cutting-edge computer technology with massive parallelism, and even then some approximations must be introduced to make the computations feasible. These results are a remarkable embodiment of the vision that elements of reality can be reproduced by purely conceptual constructions – "Its from Bits" – because the underlying theory, based on profoundly symmetrical equations, contains very few adjustable parameters.

But simply having a computer spit out the answer, after gigantic and totally opaque calculations, does not satisfy our hunger for understanding. It is particularly unsatisfactory in the present case, because the answer appears to be miraculous. The computers construct for us massive particles using building blocks – quarks and gluons – that are themselves massless. The equations of QCD Lite output Mass without Mass. It sounds suspicious, like Something for Nothing. How did it happen?

The key, again, is asymptotic freedom. Previously, I discussed asymptotic freedom in terms of hard and soft radiation. Hard radiation is rare, soft radiation is common. There is another way of looking at it, mathematically equivalent, that is useful here. From the classical equations of QCD, one would expect a force field between quarks that falls off as the square of the distance, as in ordinary electromagnetism (Coulomb's Law). Its enhanced coupling to soft radiation, however, means that when quantum mechanics is taken into account, a bare" colour charge, inserted into empty space, will start to surround itself with a cloud of virtual colour gluons. These colour gluon fields themselves carry colour charge, so they are sources of additional soft radiation. The result is a self-catalysing enhancement that leads to runaway growth. A small colour charge, in isolation, builds up a big colour thundercloud.

All this structure costs energy, and theoretically the energy for a quark in isolation is infinite. That is why we never see individual quarks. Having only a finite amount of energy to work with, nature must find a way to short-circuit the colour thundercloud catastrophe. One way is to bring in an antiquark. If the antiquark could be placed right on top of the quark, their colour charges would exactly cancel each other, and the thundercloud would never get triggered. There is also another more subtle way to cancel the colour charge by bringing together three quarks, one of each colour.

In practice neither of these cancellations can be exact, however. Quarks obey the rules of quantum mechanics. It is wrong to think of them simply as tiny particles; rather, they are quantum mechanical wavicles. Quarks are subject, in particular, to Heisenberg's Uncertainty Principle, which implies that if you try to pin down their position too precisely, their momentum will be wildly uncertain. To support the possibility of large momentum, they must acquire large energy. In other words, it takes work to pin quarks down. Wavicles want to spread out. So there is a competition between two effects. To cancel the colour charge completely, we would like to put the quark and the antiquark at precisely the same place; but those wavicles resist localisation, so the cancellation comes at a price.

A number of stable compromise solutions can be found, where the quark and the antiquark (or three quarks) are brought close together but are not perfectly coincident. Their distribution is described by quantum mechanical wave functions. Each possible stable wave-patterns corresponds to – indeed, in a profound sense *it is* – a different kind of particle that you can observe. There are patterns for protons and neutrons, and for each entry in our whole Greek and Latin smorgasbord. Each pattern has some characteristic energy, because the colour fields are not entirely cancelled and because the wavicles are somewhat localised. And that energy, through Einstein's $m = E/c^2$, is the origin of mass.

Past and future

A similar mechanism, though much simpler, works in atoms. Negatively charged electrons feel an attractive electric force from the positively charged nucleus, and from that point of view they would like to snuggle right on top of it. Electrons are wavicles, though, and that inhibits them.

The result, again, is a series of possible compromise solutions. These are what we observe as the energy levels of the atom. When I give the lecture on which this article is based, at this point I use Dean Dauger's marvellous "Atom in a Box" programme to show the lovely, almost sensuous patterns of undulating waves that describe the possible states of that simplest of atoms, hydrogen. I hope you will explore "Atom in a Box" for yourself. (You can link to it at http://www.dauger.com.)

In its absence, I shall substitute a classic metaphor. The wave patterns that describe protons, neutrons and their relatives resemble the vibration patterns of musical instruments. In fact, the mathematical equations that govern these superficially very different realms are quite similar. Musical analogies go back to the prehistory of science. Pythagoras, partly inspired by his discovery that harmonious notes are sounded by strings whose lengths are in simple numerical ratios, proposed that "All things are Numbers". Kepler spoke of the music of the spheres, and his longing to find their hidden harmonies sustained him through years of tedious calculations and failed guesses before he identified the true patterns of planetary motions. Einstein, when he learned of Bohr's atomic model, called it "the highest form of musicality in the sphere of thought". Yet Bohr's model, wonderful as it is, appears to us now as a very watered down version of the true wave-mechanical atom; and the wave-mechanical proton is more intricate and symmetric by far!

Mass, a seemingly irreducible property of matter, and a byword for its sluggishness and resistance to change, turns out to emerge from a harmonious interplay of symmetry, uncertainty, and energy. Using these concepts, and the algorithms they suggest, pure computation outputs the numerical values of the masses of particles that we observe.

In conclusion, let me emphasise that our understanding of the origin of mass is by no means complete. We have achieved a beautiful and profound understanding of the origin of most of the mass of ordinary matter, but not of all of it. The value of the electron mass, in particular, remains deeply mysterious even in our most advanced speculations about the grand unification of fundamental forces and string theory. And ordinary matter, we have recently learned, supplies only a small fraction of the mass in the universe as a whole. More beautiful and profound revelations surely await discovery. We continue to search for concepts and theories that will allow us to understand the origin of mass in all its forms, by unveiling more of nature's hidden beauty. ■

COVER STORY

The key to the world of atoms

The unravelling of the mystery of Brownian motion a century ago by Einstein brought to an end all debate on whether atoms really existed or they were merely mental constructs.

V. BALAKRISHNAN

IMAGINE an enormous pumpkin floating in the vacuum of outer space in the middle of a dense swarm of the tiniest of mustard seeds that ceaselessly bounce randomly off each other and the pumpkin. What kind of motion would the pumpkin exhibit?

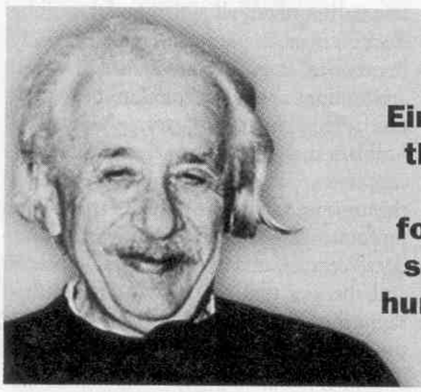
This scenario is not just a bit of idle speculation. Scaled down appropriately in space and time, this is a crucial question about how matter comprising an extremely large number of individual atoms behaves under certain conditions. The mustard seed is replaced by a molecule of water, a tiny object about a ten-billionth of a metre in size. (A billion is a thousand million.) The pumpkin could be a grain of pollen, about a millionth of a metre in size, a giant in relative terms. Typically, the mass of a pollen grain would be something like a hundred billion billion times that of a molecule. Examining under a microscope the motion of pollen grains suspended in water, this was how the Scottish botanist Robert Brown, in 1827, made the first systematic experimental study of what has come to be known as Brownian motion. The "ceaseless and chaotic dance" of the pollen grains was a truly astonishing phenomenon. Although the phenomenon had been observed even earlier, it was not clear whether any 'life-force' or biological effects were involved. Brown's observations ruled out any such biological origin of the motion.

In the years that followed, it became clear that internal motions in the liquid were somehow responsible for the motion. But there was no satisfactory explanation either for the apparently perpetual motion of the Brownian particle, or for the irregularity of its trajectory. The conundrum was unravelled by the 26-year-old Albert Einstein in his doctoral dissertation and in the seminal papers he wrote on it in 1905, the *annus mirabilis* of physics. Like the other two major themes (the light quantum and special relativity) upon which Einstein's golden touch fell in this miraculous year, this work, too, was truly the key to a vast empire of knowledge.

Going back to our analogy, the pumpkin *does* move under the constant buffeting of the mustard seeds, contrary to what we might have guessed at first sight. But surely it would never really get very far, because the seeds hit it randomly from all directions, and the pumpkin is an enormous object compared to the seeds? Wrong again. The almost imperceptible effects of the tiny but numerous and incessant collisions would cause it to tremble and jiggle about in a highly irregular fashion. These jiggles would occur on a hierarchy of scales: in principle, the graph of its path would be extremely jagged, and would remain so even if the resolution used in sketching the path were made finer. When averaged over all possible directions of motion, of course, the different displacements of the pumpkin from its starting point would tend to neutralise each other – because a step in any direction is as likely as an equally long step in the opposite direction. There can therefore be no particular *direction*, relative to its starting point, in which the pumpkin is more likely to fir itself than any other direction, at any give time. But, given sufficient time, the pum kin might find itself at quite a *distance* fro where it started – in precisely the same wa as it is possible to lose a substantial fortur over a period of time by continually placin small "can't-lose-much" bets, as many hav found to their chagrin! In fact, it turns ou that the average value of the *square* of th pumpkin's distance from the start increase steadily, being exactly proportional to th time for which we follow its motion. Ein stein's deep insight lay in recognising tha this average or mean squared distance, rath er than the velocity of the particle, was th quantity to be studied and measured i such random motion.

Incredibly enough, in the century tha has elapsed since then, it has turned out tha the mathematical analysis of this random irregular motion is the fundamental paradigm for a staggeringly large number of phenomena in subjects ranging from astronomy through economics and meteorology to zoology!

Einstein's own interest in the problem arose from a deep-seated conviction that atoms were real, that their sizes and properties could be experimentally determined, and that their populations in ordinary bits of matter, albeit astronomically large, could be estimated reliably. Using ingenious arguments involving kinetic theory and the dynamics of random molecular motion on the one hand, and heat and thermodynamics on the other, Einstein correctly explained the phenomenon. In the process, he showed how its observation could be used to determine the typical sizes of molecules – about a ten-billionth of a metre, as we have already mentioned. It could also be used to determine their number in a piece of matter under so-called 'standard' conditions of temperature and pressure – known as Avogadro's number, this is an astronomically large quantity, about a hundred thousand billion billion. Einstein's predictions were tested and thoroughly vindicated within a few years after they were made. This marked the end of all debate on whether atoms really existed or they were merely convenient mental constructs, once and for



Newton, Darwin and Einstein, when they scaled their respective heights, changed something forever. Their discoveries separate distinct eras in humankind's understanding of the universe.

Playing the violin in his study in Princeton, New Jersey, in this August 23, 1944, photo. His fondness for music found expression through the violin, which he learnt to play at the age of six.

all. The famous physicist Richard Feynman once opined that if humanity were to face cataclysmic destruction, while being permitted to pass on a *single* piece of knowledge to survivors to enable them to build a civilisation afresh, that knowledge would have to be the fact that matter consisted of atoms. In the light of this profoundly insightful remark, the importance of Einstein's breakthrough cannot be overstated.

What is even more remarkable is that Einstein used his uncanny instinct for the physics of the problem to explain Brownian motion quantitatively, carefully avoiding the pitfalls arising from the subtleties of the random processes representing Brownian motion in the strict mathematical sense, even though he was not aware of the relevant rigorous mathematics itself at the time. With the passage of time, it has become possible to gauge Einstein's true strengths with something approaching dispassionate objectivity, on the basis of his total contribution to several areas of physics, such as statistical mechanics, quantum physics, relativity and gravitation. There can be no doubt that he had the most exceptionally deep insight into fundamental concepts in physics such as the role of fluctuations, symmetry, invariance and causality, among others.

How has the analysis of Brownian motion (or a random walk, as a version of it is called) and of its subsequent generalisations contributed to human knowledge? Even a minute part of the remarkably diverse list of applications that have emerged over the past one hundred years is quite astounding. The random processes representing Brownian motion and its off-shoots are relevant to the dynamics of objects as varied as polymers in solution, chemically reacting molecules, neutrons in a nuclear reactor, clouds, sand piles, avalanches, insect swarms, animal herds, and star clusters, to techniques of computation, to fundamental issues in the theory of probability, quantum mechanics and quantum field theory, to the fluctuations of the stock market, and so on, apparently endlessly. It is interesting to note that, in the case of Brownian motion, too, the development of the relevant underlying mathematics actually preceded its incorporation into the realm of physics. As we have said, Einstein himself seems to have been completely unaware of these mathematical results, and so these did not presage Einstein's work by any means. By 1900, fully five years ahead of Einstein, Louis Bachelier had worked out substantial parts of it in his doctoral thesis, in connection with an attempt to model the fluctuating prices of shares in the stock market. Although Bachelier's work did not receive the attention it deserved for some time, it was really the progenitor of many deep results in the theory of probability in the hands of brilliant mathematicians such as Norbert Wiener and A.N. Kolmogorov. (In fact, Brownian motion is also called the Wiener process in the mathematical literature.) A hundred years later, we have come full circle. The application of the theory of probability and random processes to precisely the same class of problems as Bachelier considered, namely, in finance, is a major current preoccupation.

A century after 1905, with the benefit of hindsight, what can we say about Einstein's scientific achievements in 1905, and how do these compare with other stupendous human achievements? One may accept the judgment made by Abraham Pais in his definitive biography of Einstein: "No one before or since has widened the horizons of physics in so short a time as Einstein did in 1905." However, it is almost impossible (and perhaps ultimately irrelevant) to try to make a comparison between the highest peaks of excellence when these are widely separated in time and circumstance. But human interest in records is insatiable, and leads us to ask: Can we identify the most intense and sustained mental effort by a single person leading to the most profound results? A unique answer cannot be given. Newton, Darwin and Einstein, each at the peak of his creativity, would certainly be in the exclusive club that we may accept, as a more meaningful compromise, in place of any single person. When they scaled their respective heights, they changed something forever. Their discoveries represent watershed events for the human race itself, as they separate distinct eras in humankind's understanding of the universe in which it lives, and of its place in it. It is comfortingly salubrious to ponder over the fact that these are watersheds in a far more profound sense than mere political events – however tumultuous the latter may appear to be when they occur, or even in the long run, for that matter. After all, Ozymandias wasn't Archimedes. ■

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Space, time and Einstein

What exactly did Einstein do? Why was it important for physics then? Why does it continue to be of lasting significance for physics today?

RAJESH GOPAKUMAR

IT is somewhat ironic to pinpoint the moment of birth of an idea that has reshaped our very notions of time and space. Even its originator, Albert Einstein, could not have anticipated that his discovery of the Special Theory of Relativity would itself become a marker in historical time. As we celebrate its centenary this year, let us revisit Einstein's discovery, viewing it also in the context of history, through three questions:

What exactly did Einstein do? Why was it important for physics then? Why does it continue to be of lasting significance for physics today?

Einstein and space-time

It is conventional to state that relativity completely altered our concepts of space and time. So what exactly did Einstein do in 1905 which was so radical? In one sentence, the answer is: *he placed the physically measured notion of time on essentially the same footing as that of space.*

To understand more fully what that means, let us look closer at our notion of space. From early childhood, we apprehend the three-dimensionality of the space around us. Though "up" may look different from "right" and "down" from "left", we do not think of the various directions in space as *intrinsically* different. Especially in an age of visuals from outer space, we can readily imagine even the terrestrial distinctions between "up", "down" and so on disappearing. In other words, we take it for granted that the three dimensions of space are on the same footing. This fact has some immediate consequences in our day-to-day experience, which we do not often appreciate.

In particular, when observing objects or events around us, we can orient ourselves in any arbitrary way in these three dimensions. For instance, we might be standing upright, lying down or performing a *yogic asana* on our heads. In all these cases, we realise that our visual perspective of any given object will differ depending on the orientation we have chosen. At the same time (and this is very important), we also know how to take into account this effect of perspective. We do not get confused looking at a table from different angles; we know it is the same table.

What we can abstract from these facts of our everyday experience is the following. First, we can "mix" up different directions in space by changing our orientation so that what is up for me may be to your left. More generally, this manifests itself in altered perspectives of objects. Second, though there can be these differences in perspective, we nevertheless have a certain mental apprehension of objects which is *invariant* under changes of orientation.

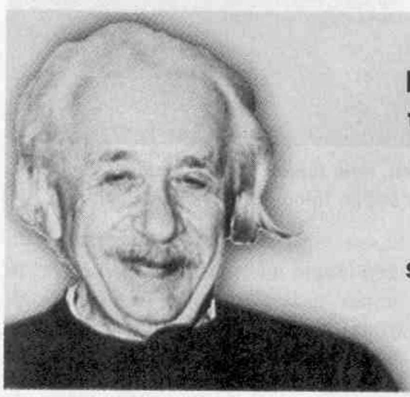
Einstein's radical advance, as we have said, was to propose that time is also, essentially, on the same footing as these three dimensions of space. Hence the notion of a four-dimensional combined space-time. This is not something rooted in our daily experience (and for a very good reason as we shall come to soon).

We shall later describe the background for arriving at this postulate. For the moment, let us just accept this proposal at face value and describe some of its striking consequences by analogy with our understanding of space. Just as we can move freely in the three directions of space by orienting ourselves differently, let us assume that there can be observers who can be "oriented" differently in space *and* time. Hence, the notions of space and time can also get "mixed" with each other, just as the different directions in space could mix up when changing orientation. This is a startling consequence simply of accept that space and time can be on the sa footing.

One immediate casualty of this p posal is the notion of an absolute ti which is the same for all observers. Obse ers oriented differently in *space-time* wo measure time intervals, by their respect clocks, differently from each other. Thi the effect known as relativistic time d tion. It is analogous to a difference in s tial perspective whereby objects can app contracted along any *one* spatial directi depending on orientation.

More surprisingly, the notion of o event occurring first and another later time can also be something dependent o the observer's orientation in space-time.

In particular, events measured to b simultaneous by one observer would nc necessarily be so for another. As a rougl spatial analogy, consider several people sit ting around a circular table. There is n absolute notion of who is farthest or clos est. Someone may be closest as measurec from the wall, while another may be closes as measured from the door. Two person may be sitting at equal distance from one observer but not from another. It all depends on where you choose to view the table from. Similarly, there can be events in time whose ordering depends on the orientation of the observer in space-time. There is no contradiction here as long as it applies to those events that can have no causal influence on each other. If one event can causally influence a second event, it actual-



It was Einstein's insight that two observers who are moving with respect to each other with a uniform velocity should be thought of as oriented differently in space-time.

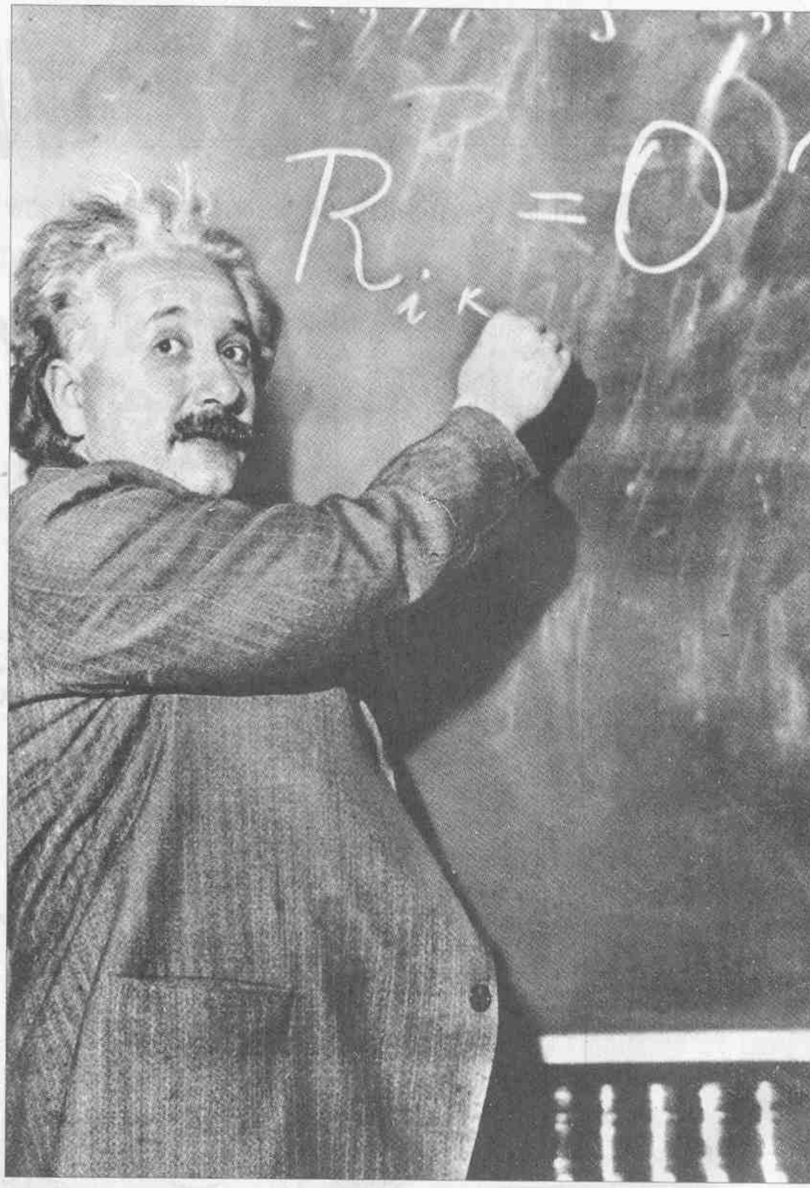
ly turns out that the first will always be before the other for all observers however differently oriented they might be in space-time. In other words, the notion of being able to causally affect another event is something invariant, as it should be. In any case, by viewing time on the same footing as space, Einstein's proposal upset deep-seated notions of time such as the absolute nature of simultaneity.

It affected certain notions of space as well. Another consequence of treating space and time on the same footing is that lengths (such as those of a rigid rod), too, would be measured differently by observers differently oriented in space-time. This would be so since distances in space alone (like intervals in time) are not something invariant in space-time as a whole. While we can readily visualise two observers who are differently oriented in space, how are we to think of two observers who are differently oriented in space-time? It was Einstein's insight that two observers who are moving with respect to each other with a *uniform velocity* should be thought of as oriented differently in space-time. We do not, however, see very much mixing up of space and time when we move on a train or even a plane. The reason is that with the small terrestrial velocities that we experience, we do not alter our orientation in space-time by too much. Only when velocities become comparable to the speed of light, which is 300,000 kilometres a second, do the effects of different orientation in space-time become noticeable.

This new situation in space-time can once again be understood by analogy. If we were fixed to a particular position and orientation in space and could only just nod our head ever so slightly from side to side, we would not have to take into account at all the effects of different perspectives in space. It would then be initially quite disorienting for us to learn that perspectives can differ dramatically if we were able to shift our orientation more than the tiny amount we were used to. The notion that we can be very differently oriented in space-time and view events in very different perspectives is similarly a radical departure from what was known before through our limited experience.

At this stage a warning is appropriate. "Everything is Relative" is often the profoundly misleading conclusion drawn from the above observations on space and time. It is important to realise that just as we can deal with different spatial perspectives and yet apprehend the invariant nature of an object like a table, the same can be done with events in space-time. Different observers in relative uniform motion may thus view events in space-time from different orientations, but nevertheless arrive at invariant conclusions about physical phenomena. Everything is *not* relative.

AP



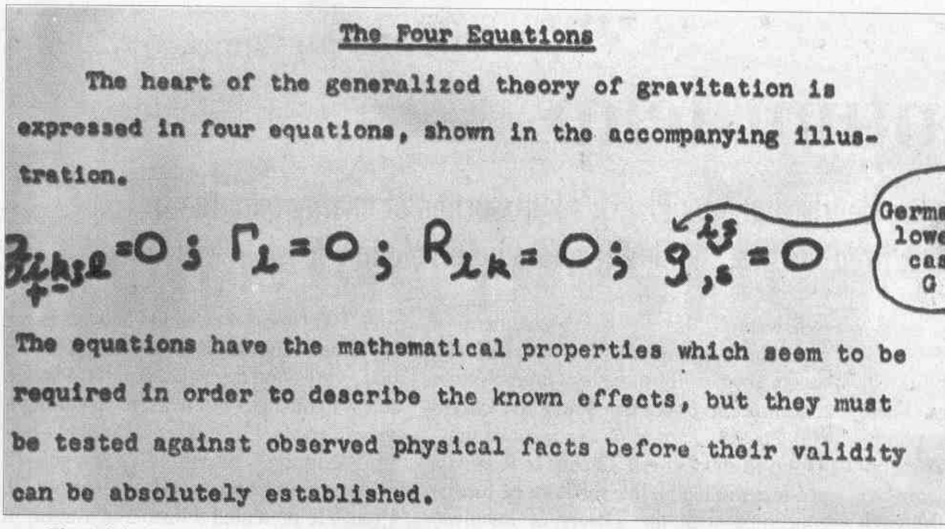
Einstein writes an equation for the density of the Milky Way at the Carnegie Institute, Mt. Wilson Observatory headquarters in Pasadena, California, in this January 14, 1931 photo.

Einstein and the physics of his time

The reader has not been given any inkling so far as to why Einstein conceived these new concepts of space-time and how it helped transform the physics of his time. It is thus important to have some appreciation of this to avoid the misconception that these notions arose purely as a flight of the imagination.

On the contrary, Einstein arrived at (or one might say, was forced into) his conclusions by seeking a resolution to a major physical puzzle of the early 20th century. This concerned the propagation of light. Michael Faraday and J.C. Maxwell's studies of electromagnetism in the late 19th century had culminated in the prediction that light was a disturbance (or wave) of the electromagnetic field. Heinrich Hertz had experimentally verified this by producing electromagnetic waves. This was to lead to the radio and other inventions.

However, from prior experience with other waves, such as waves in water or those of sound in air, it was felt that light too needed a medium to propagate in. In the case of electromagnetism, the candidate was dubbed the 'ether'. However, a problem with this proposal was that the ether was not directly observed. Also it would seem as if the speed of light would



The Four Equations

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

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

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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.

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Einstein's "generalised theory of gravitation" which attempts to interrelate all known physical phenomena and bring relativity and the quantum theory into a single system.

depend on one's motion with respect to the ether. In particular, in its motion around the sun, the earth would be moving with respect to the ether. However, no experiment detected any change in the speed of light either when it propagated in the direction of the earth's motion or perpendicular to it. To account for these puzzling results, people tried to attribute unusual dynamical properties to the ether whereby it could cause lengths to shrink in its direction of motion.

To appreciate Einstein's marvellous and far-reaching solution to this conundrum, we need to distinguish between *kinematics* and *dynamics*. Kinematics is simply about describing the basic aspects of motion such as the positions of objects and how these change with time. It is not concerned with the causes of motion. Dynamics, on the other hand, addresses the forces that are involved in such motion and thereby tries to explain the motion. Kinematics therefore involves (implicitly or explicitly) assumptions about the geometry of space and its relation to time. These assumptions, abstracted from our perception of the world, rarely need changing. The laws of dynamics (like those of gravitation, for example) deal with specific forces and are built on these kinematic assumptions. These laws are being continually refined and modified as we learn more about the causes of different kinds of motion. To give a rough analogy, kinematics is akin to the basic note structure in any particular system of music. Dynamics is more akin to the different ragas and compositions that can be built on that underlying framework. The latter evolves over the course of history while the former rarely changes.

The basic kinematic assumption underlying physics since Isaac Newton had been that of an Absolute (three-dimensional) Space and a separate Absolute Time which is the same for all observers, whatever their individual state of motion. Einstein's genius was in recognising that this kinematic assumption was flawed, and only approximately valid in circumstances where the velocities are small compared to the velocity of light. He proposed a new kinematical rule that told one how measurements of space and time by one observer would be related to another in uniform motion with respect to the first. This rule put space and time on the same footing in the sense that has been explained earlier, namely that the two observers are merely oriented differently in four-dimensional space-time.

With this rule, all observers in uniform motion would measure the same speed of light. Thus Einstein proposed a kinematical solution to what seemed like a problem of the dynamics of light's propagation in the ether. In fact, Einstein's solution showed that there was no need to propose this unobserved medium. All the facts about electromagnetism fitted in neatly with his new kinematical rules. Moreover, as mentioned earlier, when relative velocities of observers are small compared to that of light, these rules reduce to what we expect from the Newtonian kinematic assumption of a separate space and time.

The new kinematics had a number of other immediate consequences. Among the most famous is the equivalence of energy and mass encapsulated in the $E = mc^2$ relation. Again, because the origin of this relation is kinematical, it applies to all objects, whatever be their constitution or the nature of the forces acting on them. Thus Einstein's solution of the ether puzzle had an impact far beyond the particular dynamical context in which that puzzle had arisen.

Einstein and the physics of our time

The kinematic framework of physics rarely changes. The year 1905 is thus quite a unique occasion, which is why Einstein's discovery continues to be a lasting legacy to this day. In the intervening century, while there have been other upheavals in physics such as quantum mechanics and many new discoveries from the sub-nuclear regime to intergalactic scales, we have yet to see a need for a modification to the kinematic framework proposed by Einstein. On the contrary, we have much greater access to velocity regimes close to the speed of light where Einstein's mixing of space and time is dramatically validated. The scientific observer, while viewing space-time, can do far more than, figuratively speaking, being able to nod one's head just a little bit.

As far as we know, the kinematic rules proposed by Einstein are satisfied by all dynamical laws of nature. In fact, because of the absence of any evidence to the contrary, the consistency of any fundamental dynamical law with Einstein's kinematics is essential. Thus the postulates of the Special Theory of Relativity have become guiding principles in the formulation of new dynamical laws.

More generally, Einstein's emphasis on the role of symmetries and invariance percolated through the physics of the last century. It has proved immensely fruitful both in the discovery of new laws and in the deeper appreciation of existing ones.

Einstein's later discoveries in his study of gravitation further deepened the physicist's conception of space and time. It changed the idea of space-time as a passive arena for all events and rather made space-time itself a participant. The cosmological expansion of the universe is the most striking demonstration of this idea.

To get a sense of how monumental Einstein's legacy to physics is, we merely need to recall that while we have described here one of his colossal achievements, we have not even touched on any of his other seminal contributions in quantum theory and statistical mechanics. We, the inheritors of his legacy, can only stand in quiet humility even a century afterwards. ■

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The quantum leap

Einstein was the first to realise clearly that Max Planck's introduction of energy quanta was truly revolutionary. Though Planck fired the first shot in the quantum revolution, Einstein was to lead it.

VIRENDRA SINGH

IN his house at Princeton, Albert Einstein had a few pictures and etchings. These included a drawing of Gandhi, photographs of his mother and sister Maja, besides etchings of the physicists he admired most: Isaac Newton, James Clerk Maxwell and Michael Faraday.

Newton, with his formulation of the three laws of motion and his discovery of the law of universal gravitation, laid the foundations of classical physics. He gave magisterial treatment of his system in his magnum opus *Principia* (1687), a true watershed in the human understanding of the physical world. Newton's world consisted of discrete mass particles, moving with time in the arena of space, under the influence of mutual forces. He also believed that light also consisted of discrete light corpuscles.

Later, the discovery of the phenomena of interference and diffraction of light led physicists to regard light as a wave. Since it was believed that waves need a medium for their propagation, a medium called 'luminiferous ether' was postulated for light waves. In the 19th century, Faraday introduced the concept of continuous fields, as opposed to discrete particles, like electric and magnetic fields. Maxwell's equations for these fields (1864) unified them into a single entity called the "electro-magnetic field" generated by electric charge and currents. A windfall of this unification was the prediction of electromagnetic waves, with a constant velocity which agreed with that of light. Maxwell then proposed to identify electromagnetic waves with light, thus unifying optics with electromagnetism.

At the end of the 19th century it appeared that the classical physics of Newton, Faraday and Maxwell provided a complete description of the natural world and that the end of physics was almost in sight. It was, however, the proverbial lull before the storm.

Physics underwent two major revolutions in the first quarter of the twentieth century. The origin of one of these was in the failure to detect the motion of the earth through the ether. This problem was resolved by Einstein in the Special Theory of Relativity (1905) by the banishment of ether and a thorough revision of the Newtonian concepts of space and time. Further modifications of flat space-time to a curved one led to a change in our view of gravitation in the General Theory of Relativity of Einstein (1915). We shall not be further concerned with the Theory of Relativity but will be following the second revolution, the quantum revolution, and Einstein's contributions to it.

The origins of the quantum theory

The origins of the quantum revolution lay in the problem of black body radiation. As is well known, all heated bodies emit radiation. They also absorb a fraction of the radiation falling on them. The precise amount of emission and absorption of radiation of a particular frequency depends on the nature and the temperature of the body. However, in 1859, Gustav Robert Kirchhoff showed that the ratio of emissivity to absorptivity of a body is independent of its nature and is thus a universal function, which is the same for all bodies. Further, this universal function was the same as the emissivity of a perfectly black body, a body that absorbs all the radiation that falls on it. He also showed that the radiation inside a cavity, kept at a fixed temperature, is the same as black body radiation.

In 1894, Wilhem Wien proposed an expression for this function, known as Wien's radiation law, which fitted the experimental data very well at higher frequencies.

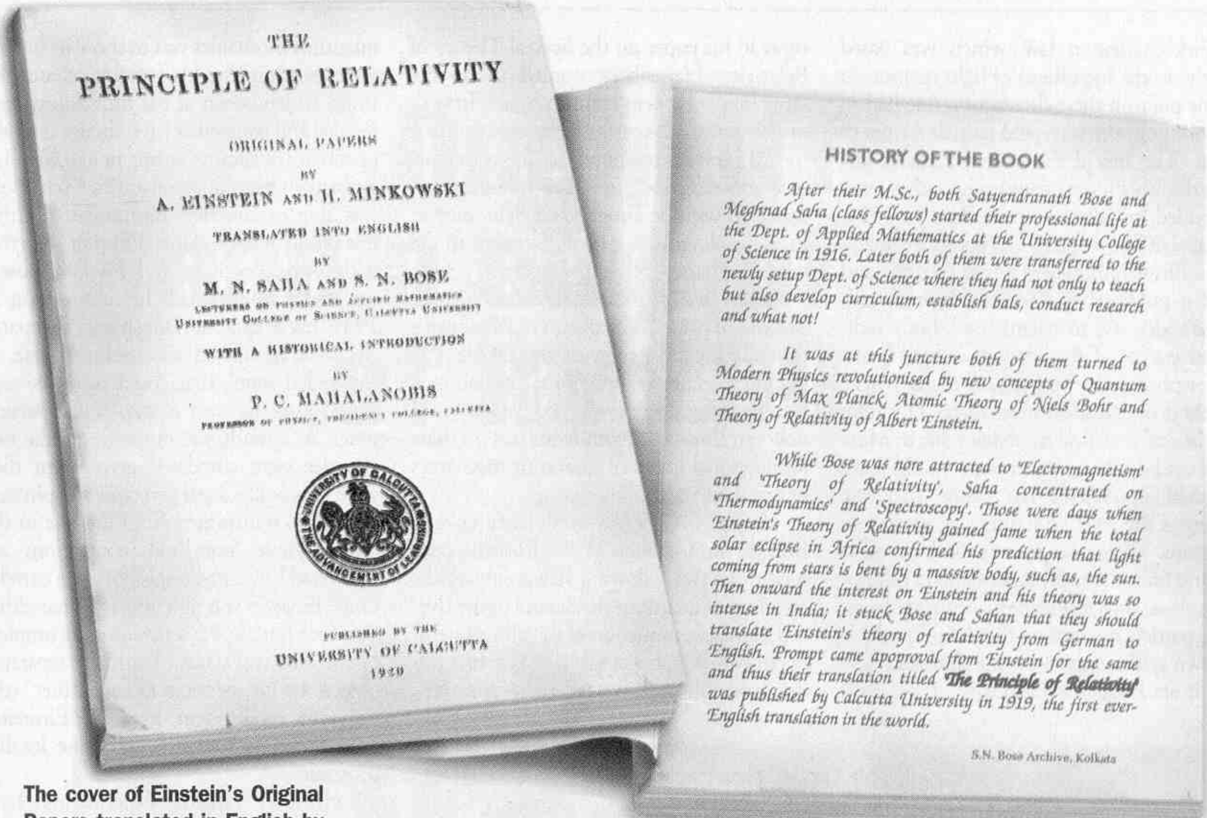
Max Planck succeeded to the chair in physics occupied by Kirchoff in Berlin in 1889. He was naturally drawn to the problem of determining the universal function of Kirchhoff. Planck's idea was to assume a simple model of the cavity walls since the black body radiation is independent of the nature of the walls. He took the wall to be made of elementary oscillators, each capable of absorbing and emitting radiation only at a definite frequency. Using Maxwell's theory he found a relation between the energy density of the black body radiation and the average energy of the elementary oscillators. Shortly after this result was announced on May 18, 1899, Lord Rayleigh derived in June 1900 another radiation law (corrected by James Hopwood Jeans later in 1905) that gave a good description of the radiation at low frequencies but failed badly for higher frequencies where Wien's law was a better description. The correct law was guessed by Planck and announced on October 19, 1900. He presented a formal derivation of the law on December 14, 1900, to the German Physical Society. This can be regarded as the birth date of quantum theory.

The radical new element in Planck's work was that his elementary oscillators, with frequency f, cannot have a continuous range of energies but can only have an energy which is an integer multiple of a quantum of energy equal to hf, where h is a constant now known as Planck's constant. Planck does not seem to have realised the revolutionary nature of his proposal. He said, "This was purely a formal assumption and I really did not give it much thought except that no matter what the cost, I must bring about a positive result."

Einstein and the 'light quantum hypothesis'

The first person to realise clearly that Planck's introduction of energy quanta was truly revolutionary was Einstein. Though Planck had fired the first shot in the quantum revolution, Einstein was to lead it now. He was 26 years of age at the time he sent his paper on "light quantum hypothesis" to the journal *Annalen der Physik* on March 17, 1905. It was his first paper on quantum theory. During this year, his *annus mirabilis*, he was also to publish epoch-making papers on Brownian motion, the special theory of relativity and $E = mc^2$, besides completing his doctoral thesis on molecular dimensions. But in a letter to his friend Conrad Habicht, written at that time, Einstein applied the adjective "revolutionary" only to the paper on the light quantum hypothesis. He first shows in this paper that the radiation law of Rayleigh and Jeans is the unambiguous prediction of classical physics. Therefore, if we have to understand the phenomenon of black body radiation, a decisive break with the concepts of classical physics is involved.

Einstein was dissatisfied with the asymmetrical treatment of matter and radiation



The cover of Einstein's Original Papers translated in English by S.N. Bose and M.N. Saha. (Right) The history of the book, from the S.N. Bose archives.

in classical physics. Matter was regarded as made of discrete particles, while radiation was described as a continuous wave field. He felt that the failure of classical physics lay perhaps in not treating radiation too as being made up of particles. But then the wave theory of radiation had had a long and successful innings. Einstein remarked in his paper, "The wave theory, operating with continuous spatial functions, has proved to be correct in representing purely optical phenomena and will probably not be replaced by any other theory. One must, however, keep in mind that the optical observations are concerned with temporal mean values and not with instantaneous values, and it is possible, in spite of the complete experimental verification of the theory of reflection, refraction, diffraction, dispersion and so on, that the theory of light which operates with continuous spatial functions may lead to contradictions with observations if we apply it to the phenomena of the generation and transformation of light."

Using Wien's radiation law, which was in good agreement with the experimental data on black body radiation at high frequencies, where the predictions of classical physics fail, Einstein found that "monochromatic radiation of small energy density... behaves... as though it consisted of distinct independent energy quanta of magnitude hf". Einstein thus introduced the hypothesis of quanta of light. He applied it to explain Stokes' law, ionisation of gas by ultraviolet light and the photoelectric effect. As Abraham Pais, the pre-eminent scientific biographer of Einstein, remarks, this was the second coming of the quantum.

Surprisingly, when Einstein discussed the theory of photoelectric effect, all the details of the phenomenon were not yet clarified through experiment, though the experimental work had been going on since the original observation of the effect by Heinrich Hertz in 1887. But by 1915-1916 the extensive experimentation of R.A. Millikan led him to say, despite his disbelief in the hypothesis of light quanta, "Einstein's photoelectric equation... appears in every case to predict exactly the observed result." Einstein was awarded the Nobel Prize for Physics for the year 1921 for this work. The announcement was made in November 1922. The discovery of the Compton effect in October 1922 finally brought about a general acceptance of the idea of light quanta.

Further development of the quantum theory

Einstein also pioneered the extension and application of the quantum hypothesis to problems in physics other than those involving radiation. In 1907 he applied the quantum hypothesis to the study of the specific heat of solids. The predictions of classical physics were in agreement with experiment at higher temperatures but failed to explain the measurements at low temperatures. Using the same hypothesis regarding the energy of the elementary oscillators as in the derivation of Planck's radiation law, Einstein provided, using the quantum hypothesis, the first model for the specific heat of solids that was in broad agreement with the experimental data. The model was later refined by Peter Debye (1912) and by Max Born and Theodore von Karman (1912, 1918).

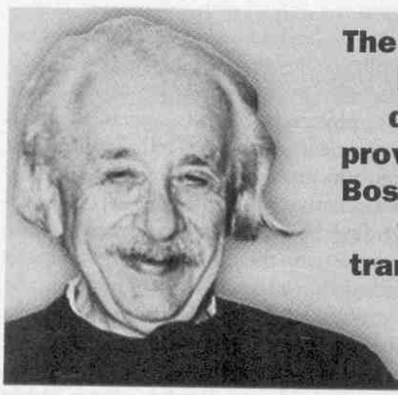
In 1917, Einstein used the method of chemical kinetics to give a new derivation of Planck's law. He also used the concept of discrete energy states introduced by Niels Bohr in 1913 when he applied quantum theory to the problem of atomic structure and spectra. Einstein recognised that in order to obtain Planck's law by this method it was crucial to consider the process of the stimulated emission of light. In this process an atom undergoes a transition from a state of higher energy to one of lower energy, a transition induced by the presence of radiation.

The possibility of the stimulated emission of light, first recognised by Einstein, is the fundamental mechanism underlying the functioning of lasers.

Bose and Einstein

Despite various attempts by Einstein and others, there was no derivation of

Planck's radiation law, which was based solely on the hypothesis of light quanta. At some point in these derivations, one had to invoke both the wave and particle nature of light. The first derivation of Planck's law based solely on the quantum hypothesis was provided by Satyendranath Bose in 1924. Bose sent his work to Einstein for evaluation. Einstein translated it into German and had it published in *Zeitschrift fur Physik*. Bose's idea was to regard black body radiation as a gas of non-interacting light quanta, or photons as we now call them, by the method of statistical mechanics. The rules of classical statistical mechanics due to Maxwell and Ludwig Boltzmann would have resulted in Wien's law. Bose therefore changed the rules of statistics as applied to photons. These rules are now understood as arising from the indistinguishability of photons. Bose thus founded quantum statistics. The particular counting that he proposed is known as Bose statistics and particles obeying it are known as bosons.



The first derivation of Planck's law based solely on the quantum hypothesis was provided by S.N. Bose in 1924. Bose sent his work to Einstein for evaluation. Einstein translated it into German and had it published in *Zeitschrift fur Physik*.

Einstein immediately saw the importance of Bose's work and applied it to material particles. As a result the new statistics proposed is also known as Bose-Einstein statistics. A prediction of this application was a new type of quantum phase transition, known as Bose-Einstein condensation, which has been experimentally observed only recently. The Nobel Prize in Physics for 2001 was awarded to Eric A. Cornell, Carl E. Wiemann and Wolfgang Ketterle for this discovery.

Foundations of quantum mechanics

The initial phase of quantum theory, which lasted from 1900 to 1924, is sometimes referred to as "old quantum theory". As we have seen, Einstein played a pivotal role here. The final formulation of quantum mechanics was achieved by Werner Heisenberg (1925), Paul Dirac (1925), and Erwin Schrodinger (1926). Heisenberg's work was inspired by Einstein's methodology of analysing the observability of space-time concepts in his paper on the Special Theory of Relativity. Heisenberg wanted to do the same for concepts in atomic physics. In view of his own work in 1909, Einstein was in a special position to appreciate the wave-particle connection. Through a triangular interaction with de Broglie and Schrodinger, Einstein played the role of godfather to the wave mechanics of Schrodinger.

Even though the mathematical formalism was in place, the problem of what quantum mechanics meant, or the problem of the interpretation of quantum mechanics as it came to be known, was wide open. From now on, Einstein's main focus was on these foundational issues of quantum mechanics rather than its applications.

At the fifth Solvay conference held in Brussels in October 1927, Einstein contrasted the two following viewpoints on the meaning of quantum mechanics in the context of the phenomenon of the diffraction of electrons through a single slit. The first was the ensemble interpretation. In this view, the quantum mechanical probability of the position of an electron gives only the probability of finding some electron in a large collection at a particular position but does not give any information about the behaviour of a single electron. This is the view to which Einstein subscribed. In contrast, the second regarded quantum mechanics as a complete theory of individual processes, according to which it is one and the same electron whose probability of being at a particular position is given by the quantum probability distribution. Needless to say, this was the view of Niels Bohr.

We thus see that the ensemble interpretation of quantum mechanics, which is in some sense the operative part of quantum mechanics, goes back to Einstein. Soon, however, Bohr's views, known as the 'Copenhagen interpretation' became the dominant one. Einstein, however, in view of his deep commitment to realism, did not favour it.

Einstein's strategy in his critique of quantum mechanics was to show its inc pleteness. Initially, his famous debate Bohr, which began at the fifth Solvay c ference and continued later, focussed on possibility of circumventing or evading I senberg's uncertainty relations. Here B was able to convince him eventually this could not be done. Einstein, toget with Boris Podolsky and Nathan Ros was more fruitful with his observation 1935 that in quantum mechanics two pa cles could be created in a combined state, 'entangled state', that could never be s arated into the sum of two single parti states. As a result, the properties of the t particles were correlated even when th were physically separated and no physi signal was transmitted from the one to t other. These 'non-local' correlations known as Einstein-Podolsky-Rosen corre tions. Einstein was able to show that eith the wave function description is incomple or the "the real states of spatially separat objects are independent of each other" (t principle of Einstein locality). Einstein predilection was to believe in the locali principle.

However, recent experiments hav shown, using John Bell's (1966) re-formul tion of Einstein locality, that this non-loca ity is an essential feature of nature. Th recent upsurge of research in the new field of quantum information, quantum com puting and quantum cryptography arise out of the exploitation of precisely thes Einstein-Podolsky-Rosen correlations. Th 'entanglement' of quantum multi-particl states, which was initially an embarrassmen even to some of the votaries of quantum mechanics, is now used as a resource in these applications. Even when in disagreement with the main trends in the interpretation of the advances in quantum mechanics, Einstein unerringly focussed on one of its most significant aspects, one that has continued relevance even to this day.

Einstein's public acclaim perhaps depends mostly on the relativity theory. But Einstein's eminent contemporary Max Born once remarked, "In my opinion he would be one of the greatest theoretical physicists of all times even if he had not written a single line on relativity." Einstein's legacy in quantum mechanics is still overwhelming.

A hundred years after his *annus mirabilis*, it is clear that Einstein belongs in the select company of Newton, Maxwell and Faraday, whom he so greatly admired. ■

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In pursuit of a dream

Einstein's thoughts went far beyond the frontiers of science: he was a symbol of the struggle for peace, social justice and socialism.

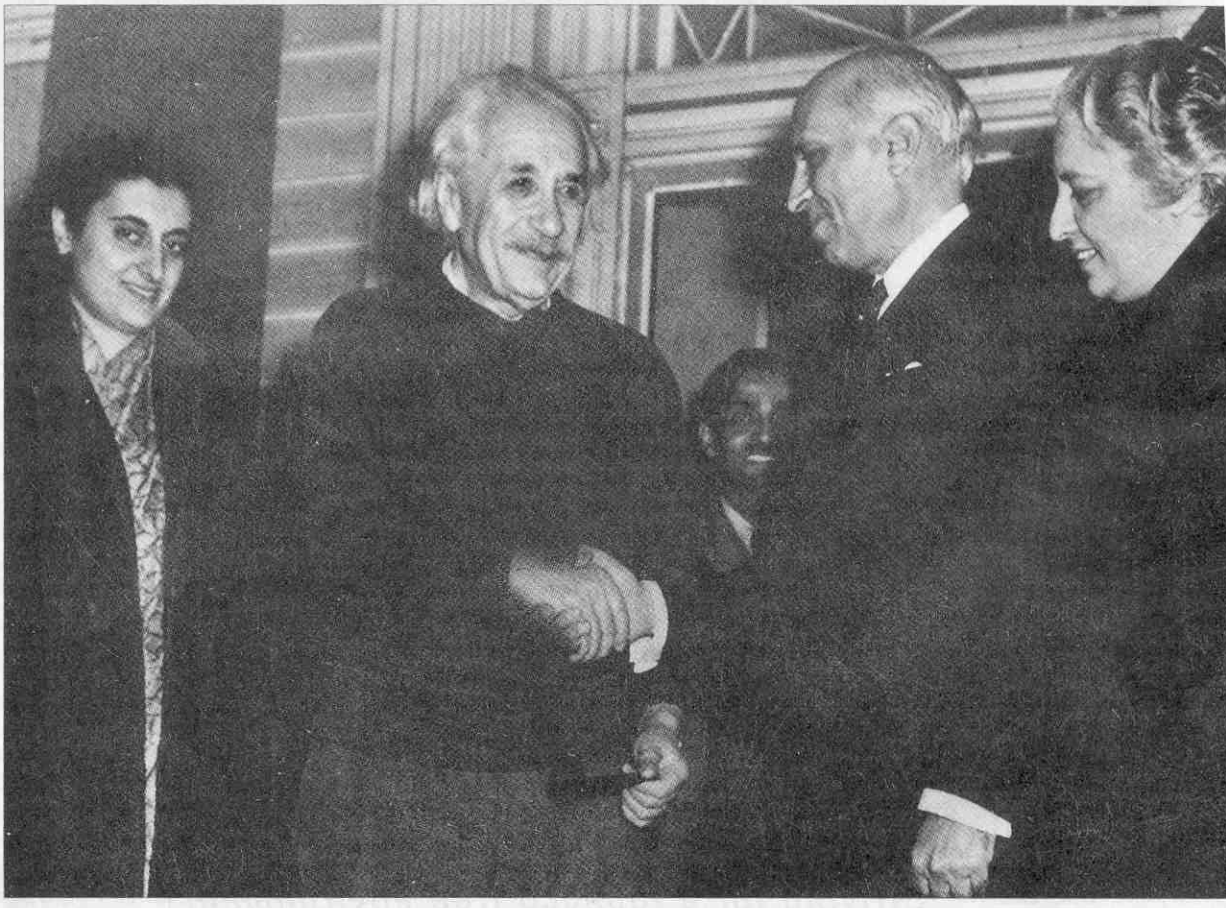
S. CHATTERJEE

A POLL conducted at the turn of the century elected Albert Einstein the 'man of the century'. The cause of his popularity was a matter of great debate and speculation. In an interview given to a Dutch newspaper in 1921, Einstein remarked that the reason was the mysterious nature of his theory, which took his audience to a mysterious world. Had he been asked the question a few years before his death, Einstein would have answered differently. Indeed, the masses of people who elected him the man of the century did so not purely for the mysteries of relativity, but also for the fact that Einstein had grown as a symbol of the fight for peace, friendship, social justice and (this may come as a surprise to many) socialism.

One aspect of Einstein's life that has been a matter of great speculation and debate is his moral responsibility for the initiation of the Manhattan Project that led to the production of the atom bomb and its subsequent use on Japan. It was a time when the Second World War was on and Germany had recorded victories in the initial phases. Peace-lovers all over the world, who had for years thought that international pressure would thwart the imperial ambitions of Germany, now considered it their duty to ensure Hitler's defeat.

Einstein, a confirmed pacifist who often said that war could not be humanised and paid glowing tributes to Gandhi, never attached any "absolutism" in the means to achieve his pacifist goals. Rather, he maintained that "organised power can b posed only by organised power" anc "the use of force is appropriate – name the face of an enemy unconditionally on destroying me and my people". I *was* one such enemy.

Though Einstein's formula $E = n$ the basic principle on which the bomb works, he had not examined in cient depth the feasibility of its practica and "indeed did not foresee that it w be realised in my time". It was thr meetings with three Hungarian refugee entists and victims of Nazi persecu namely, Szilard, Wigner and Teller, tha learnt about the advances in uranium sion that had taken place in Germ France and the United States. It was clear and "almost certain that this [bo



When Prime Minister Jawaharlal Nehru, Indira Gandhi and Vijayalakshmi Pandit visited Einstein at his home in Princeton.

could be achieved in the immediate future".

Apprehension of a German bomb was further based on the fact that if Hitler captured Belgium and had free access to its uranium, that would give Germany unlimited power to hold the world to ransom. It was believed that the German war machinery had already geared itself to this end, since the son of the German Under Secretary of State, von Weizsacker, was attached to the Kaiser Wilhelm Institute of Berlin, where some of the American work on uranium was then being repeated.

Einstein conveyed these apprehensions to President Franklin D. Roosevelt in a letter and urged that the U.S. government machinery take immediate steps to check the impending German monopoly in atomic weapons. The importance of this letter cannot be denied, but it would be a gross exaggeration to suggest that this letter planted the seeds of atomic weaponisation. The fact is that the practical possibilities of making such weapons had already been considered in several quarters in France, Britain and Germany.

Einstein once remarked, "My participation in the production of the atomic bomb consists of one single act: I signed a letter to President Roosevelt." During the course of the war Einstein's own involvement with the war efforts was rather minor, being limited to theoretical investigations on explosions and the problem of gaseous diffusion, the latter being considered as a means of producing enriched uranium. Einstein admits that his letter to Roosevelt was written in the apprehension that "Germans would make them", but when it was clear that the "enemy unconditionally bent on destroying me and my people" was on the verge of surrender the circumstance in which the use of force was appropriate had disappeared.

Einstein, like many other scientists, now pleaded that the bomb should never be used, a plea he communicated in a letter to the President. Unfortunately, President Roosevelt had died by the time the letter reached the presidential office. Roosevelt's successor, President Harry S. Truman, treated Einstein's letter, as also a memorandum of scientists, with scant respect. The plan to use the bomb had been made. As C.P. Snow remarked, with the discovery of fission, scientists had overnight become prized military resources. The war machine and the political leadership used the weapon and ignored the scientists.

Einstein, like all other scientists, learnt about the bombing of Hiroshima and Nagasaki through the press. To him "the first atomic bomb destroyed more than the city of Hiroshima. It also exploded our inherited, outdated political ideas". Scientists now considered it their duty to join the nuclear disarmament movement, to which Einstein's notable contribution came first in the form of a proposal that the U.S. and the United Kingdom share the know-how of the weapon with an international agency so that no nation had the monopoly. Subsequently, the Einstein-Russell declaration (made with Bertrand Russell the philosopher-mathematician) demanded disarmament, a cause that millions are fighting for.

Though Einstein, in his concern to defeat fascism, had expressed satisfaction at "doing anything which might be useful to the national effort", his involvement with the project or with the war efforts was kept at a minimum. This had to do with two factors. Firstly, as a scientist Einstein was a loner, while the work at the project required teamwork and secrecy. The other and more important factor was his political views. Since his Berlin days, that is, since the time of the First World War, he had made statements against free market and

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With Nobel laureate Rabindranath Tagore in 1930, at Einstein's country house near Berlin.

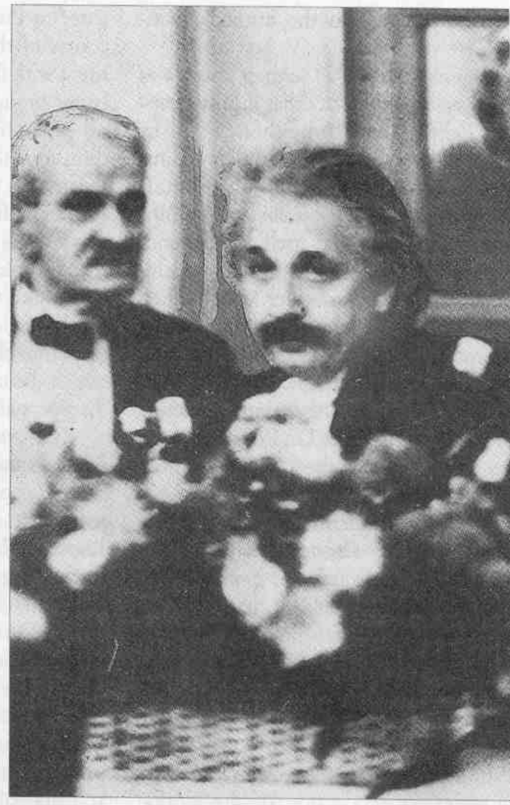
capitalism. Hence the U.S. military establishment did not take him into confidence "in view of the attitudes of people in Washington, who have studied into his whole history".

WHAT was this whole history? Einstein abhorred militarism all his life. As a youth he found the militarism in Germany to be suffocating and gave up his German citizenship and opted for Swiss citizenship. It was during the First World War that Einstein entered direct political activity. Following the invasion of Belgium by Germany, a group of 93 German intellectuals signed what it called the 'Manifesto of the Civilized World', justifying the invasion in the name of protecting German culture. Einstein, then 35, and three other intellectuals released a counter-statement – a 'Manifesto to Europeans' – arguing for the formation of the League of Nations to "unite the continent into a organic whole". He joined the New Fatherland League, a group that campaigned for the above cause even clandestinely after it was banned. The Berlin police blacklisted Einstein and the members of the group were required to take the permission of the military authorities before applying for passports.

Einstein was wary of political figures but was not indifferent to political thought. He lived through tumultuous times in an era of social upheavals. The confirmations of his General Theory of Relativity made headline news on the second anniversary of the Russian Revolution, on a day when workers barricaded his home in an insurrection against the German government. In 1919 Germany signed the inglorious Versailles Treaty, which brought untold misery to the German people, pushing them to despondency. The failure of the workers' insurrection also led to the rise of right reactionary forces that finally brought Hitler to power in 1933.

During this period Einstein had won worldwide recognition and was also awarded the Nobel Prize in Physics for the year 1921. But it was also the period when his left-wing views and pacifism became the target of attack by conservatives such as the Nazis as being a part of Jewish treason. The Theory of Relativity was condemned as a part of Bolshevik and Jewish conspiracy and he received death threats.

Einstein remained undeterred in this period and considered international cooperation between the intelligentsia of all countries as a means of better understanding among peoples. While the Nazi propaganda tried to arouse German citizens to war hysteria, Einstein expressed his indignation of military exercises, including compulsory military training. By the mid-1930s his ideas on this subject were already advanced and he said the armament industry was "indeed one of the greatest dangers that beset mankind", which with its evil hidden power of nationalism was trying to plunge the world into a war. Einstein argued that nationalisation of the war industries, such as aircraft, metal and chemicals, would mitigate the threats. Seventy years later, we can ask, has the threat receded?



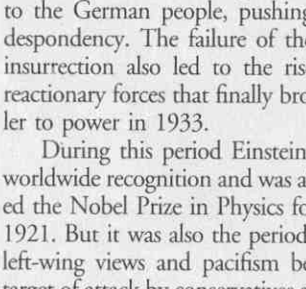
A meeting of great minds. (From left) Einstein, Lord Rothschild, one of the richest men in the world at the time, and George Bernard Shaw at a dinner in London.

Indeed, his international stature as a scientist came in useful to Einstein in espousing his thoughts. While welcoming "America and the Disarmament Conference, 1932", Einstein asked people to ponder why such conferences had failed in the past. He had himself conveyed his frustration by resigning from the Committee on Intellectual Cooperation of the League of Nations in 1923, over its inaction. In this 1932 letter, he placed free market economy as a factor for the economic chaos in the world. That was the time of economic depression in the capitalist world.

Einstein noted: "Since the amount of work needed to supply everybody's needs has been reduced through the improvement of technical methods, free play of economic forces no longer produces a state of affairs in which all available labour can find employment. Deliberate regulation and organisation are becoming necessary to make the results of technical progress beneficial to all." This was a direct attack on capitalism. Einstein noted that by American capital's unbridled forays into Europe, America "is hastening the economic and therewith the moral decline of Europe; she has helped to balkanise Europe and therefore shares the responsibility for the breakdown of political morality and the growth of that spirit of revenge which feeds on despair."

This was a part of the "whole history" of Einstein that was known to the people in Washington. Moreover, in 1942, three years after he got U.S. citizenship, he asked, "Why did Washington help to strangulate Loyalist Spain? Why has it an official representative in fascist France? ...Why does it maintain relations with fascist Spain? Why is there no really serious effort to assist Russia in her dire need? [The U.S.] Government is to a large degree controlled by financiers, the mentality of whom is near to the fascist frame of mind."

EINSTEIN'S disillusionment with the American polity sharpened deeply af-



The core issue before mankind, according to Einstein, was that "the world was promised freedom from want but large parts of the world are faced with starvation, while others are living in abundance".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ter the Second World War. After the mass murder in Hiroshima and Nagasaki, he said: "All of us who are concerned for peace and triumph of reason and justice must today be keenly aware how small an influence reason and honest goodwill exert upon events in the political field." But despondency offered no solution and "without tireless efforts of those who are concerned with the welfare of humanity as a whole, the lot of mankind would be still worse than in fact it even now is."

The core issue before mankind, according to Einstein, was that "the world was promised freedom from want but large parts of the world are faced with starvation, while others are living in abundance". "The economic anarchy of capitalist society as it exists today is, in my opinion, the real source of evil," since "the entire production is carried for profit, not for use. The technological progress produces an army of unemployed, rather than in easing of the burden of work for all." Also, "unlimited competition leads to a large waste of labour, and to the crippling of social consciousness of individuals. ...This crippling of individual, I consider the worst evil of capitalism... An exaggerated competitive attitude is inculcated into the student, who is trained to worship acquisitive success as a preparation for his future career."

To Einstein, the future lay in socialism, to take mankind away from "the predatory phase of human development". But the question remained as to how the socialist economy should work? Einstein felt that the present science of economics, developed in the predatory ideology of capitalism, was incapable of throwing light on the socialist society of the future. Thus Einstein did not look at economics as being divorced from politics but saw the two being coupled by political economy. As regards socialism, he was conscious of the practical difficulties but thought that the problems of socialism must form the subject of active intellectual debate.

Einstein's radical views received hostile comments from a section of the American press. With the rise of McCarthyism, these grew into targeted attacks that questioned his loyalty to the country of his adoption. These first began with his involvement with the disarmament movement and his advocacy of the sharing of nuclear secrets with a world government was considered tantamount to surrendering these strategic military secrets to the enemy.

The attacks became sharp and intense after Einstein gave a call to citizens and intellectuals to refuse to testify before the State Internal Security Committee, which was formed during Truman's presidency. The government had prepared a list of allegedly subversive groups and individuals who had communist loyalty and also barred visas to many foreign scientists and intellectuals on account of their "communist sympathies". As a part of this witch-hunt the Rosenberg couple (Julius and Ethel Rosenberg) were executed on the electric chair in July 1953 on the charge that they had spied for the Soviets. Einstein sent a prayer to the President, asking that clemency be given to the Rosenbergs.

William Frauenglass, an English teacher in a school, refused to testify before the committee and this act of defiance invited the threat of dismissal. In a letter to Frauenglass, which was released to the press, Einstein supported Frauenglass' forthright stand against "reactionary politicians", who "are now proceeding to suppress the freedom of teaching and to deprive of their positions all those who do not prove submissive". Einstein considered Frauenglass' refusal to appear before an "inquisition" to be perfectly legal as such an "inquisition violates the spirit of constitution".

Soon the attacks on Einstein became extremely severe. Senator Joseph McCarthy threatened that those who took Einstein's advice of boycotting the security committees would be seen as "enemies of America" and some Senators demanded that Einstein be deported for the crime of propagating communist ideas. When both the houses passed a Bill outlawing the Communist Party, Einstein declared, "it is nonsense" because such a law violated individual freedom.

Along with many intellectuals, one of the victims of the anti-communist witch-hunt was Robert Oppenheimer, the scientist who directed the operations at the Manhattan Project. With time, Einstein's condemnation of McCarthyism and its attack on the intellectual liberty of the individual became more vocal. He pointed at the absurdity that "the fear of communism has led to practices which have become incomprehensible to the rest of the civilised mankind and expose our country to ridicule." He declared, "If I were a young man again and had to decide how to make a living, I would not try to become a scientist or scholar or teacher. I would rather choose to be a plumber or peddler, in the hope of finding the modest degree of independence still available under present circumstances."

This incrimination of those who suppress human rights came with a call for eternal vigilance and struggle for the realisation of a dream: since a large part of history is replete with instances of struggle for human rights, "an eternal struggle, in which a final victory can never be won. But to tire in that struggle would mean the ruin of society".

That legacy will continue to remain. ■

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