In this issue

The Legacy of Albert Einstein (1879–1955)

The epoch-making 1905 papers of Albert Einstein, mark a turning point in the history of physics and also the history of mankind. In this respect he shares a platform with Galileo and Newton who gave us the basic formulation of mechanics in terms of forces and accelerations, and with Faraday and Maxwell, who introduced the notion of fields in space and time.

In this hundredth anniversary year we look back and recall the main threads Einstein wove into the tapestry of physics. This collection of articles, 'The legacy of Albert Einstein' (**page 2034–2146**), presents developments whose initiation can be found in the works of Einstein. We have not restricted ourselves to the 1905 papers, but include all his major contributions to physics. Since Einstein was a major public figure of the 20th century we also include this aspect in the collection.

One cannot fail to note that one of the most important legacies of Einstein, is the fact that he did not make any conscious value differentiation between different areas of physics. He was equally at home with relativity, geometry, radiation theory, Brownian motion, statistics, molecular physics and so on. There was his quest for frameworks and general principles within which the laws of nature operate, and there was an equally important quest to see how these laws manifest themselves in the world around us. In a deep sense these activities are inevitably mixed up in the grand enterprise to understand our world.

We present a glimpse of the scientific contribution of Einstein, which will hopefully provide an overall background to the articles in the special section.

Einstein's *Annus Mirabilis:* Five papers that changed the world

The 1905 papers sowed the seeds of both revolutions of 20th century physics: Relativity and Quantum Theory. Before Einstein there were Newton's laws of mechanics and Maxwell's equations of electrodynamics. Thermodynamics was a well established subject and there was Boltzmann's microscopic formula for entropy.

Brownian motion and the reality of atoms

Einstein's doctoral dissertation on molecular dimensions, followed by his famous statistical formula for the motion of suspended 'Brownian' particles, gave a beautiful method of calculating Avogadro's number and the size of molecules. Using this framework, the existence of the underlying molecular structure of matter was experimentally concluded beyond doubt, notably by the work of Jean Perrin. Satya Majumdar (**page 2076**) summarizes Einstein's original work and its applications to physics, probability theory and computer science.

Einstein in his study, Berlin, 1912. Courtesy of the Leo Baeck Institute, New York.

The light quantum hypothesis

Einstein put forth the daring hypothesis, that light has particulate properties ('a kind of molecular structure in energy'). His heuristic principle stated that light is created and annihilated in discrete quanta in its interaction with matter. He suggested testing his proposal using the photoelectric effect. This was a revolutionary idea, because it was in absolute contradiction with Maxwell's theory of the continuously varying electromagnetic field that describes pure radiation. His conviction in the verity of thermodynamics and in Boltzmann's formula led the way. Virendra Singh (**page 2101**) reviews the history of the light quantum.

Special relativity

'The electrodynamics of moving bodies', is the paper on special relativity. In one fell swoop Einstein replaced all mechanical explanations (and other attempts) of the constancy of the speed of light, irrespective of the motion of the source, by asserting a symmetry principle which all laws of nature must conform to! Thus was born special relativity and a new kinematic framework for physics. Maxwell's equations are true but Newton's mechanics had to be replaced. At the age of 16, while in Arrau, Einstein had asked, 'If I pursue a beam of light with velocity c, I should observe such a beam of light as a spatially oscillatory electromagnetic field at rest' (ref. 1, p. 53). This mystery was resolved by special relativity: one is never at rest with respect to light! Subsequently, he derived his celebrated $E = mc^2$, which is probably the most popular scientific formula of our times.

Einstein's magnum opus: General Relativity

The special relativity paper has no references! There is an apparent ease with which conclusions emerge in this paper. The logic seems flawless and unbreakable. Special relativity deals with special reference frames in constant uniform motion with respect to each other and also does not incorporate the instantaneous law of gravitation. Einstein set out to rectify these seemingly unrelated shortcomings.

In 1907, in his own words (ref. 1, p. 67), 'Now it came to me: The fact of the equality of inert and heavy mass, i.e. the fact of the independence of the gravitational acceleration of the nature of the falling substance, may be expressed as follows: In a gravitational field (of small spatial extension) things behave as they do in a space free of gravitation, if one introduces in it, in place of an "inertial system", a reference system which is accelerated relative to an inertial system'. Einstein calls this the happiest thought of his life. In this thought he identified the gravitational force with accelerations: the fall that we attribute to the earth's gravity is no different from the forward fall we experience when we jam the brakes of a car!

The next big step in 1912 was the realization that spacetime is curved and not flat! The search for the correct, generally covariant, equations of general relativity in the framework of Riemannian geometry took many more years. The final version of the field equations of gravitation was presented to the Prussian Academy on 25 November 1915. They are $R_{ij} - \frac{1}{2} R g_{ij} = 8pGT_{ij}$.

The discovery of these equations was an extraordinary struggle, fraught with errors and corrections. It is very encouraging and inspiring to see how the great Einstein struggled to discover these equations. He did not have the benefit of knowing the deep underlying symmetry principle hidden in the equations he was to discover! This realization was almost postfacto. The symmetry followed from the equations rather than the other way around, as most textbooks on general relativity have us believe. In a lecture to the University of Glasgow in 1933, Einstein said (ref. 2, p. 257): 'The years of searching in the dark for a truth that one feels but cannot express, the intense desire and the alternations of confidence and misgiving until one breaks through to clarity and understanding are known only to him who has experienced them'.

As is well known the predictions of the general theory of relativity were eventually vindicated by experiment. Subsequently Einstein went on to find that his equations support gravitational waves. In 1917 he proposed a cosmological solution by including the cosmological constant (dark energy in today's parlance). This work laid the foundations of cosmology in the framework of general relativity. Jayant Narlikar (**page 2114**) traces the early development of cosmology. Subir Sarkar (**page 2120**) gives an observational perspective of modern cosmology, and points to the fundamental problems of dark matter and dark energy. B. S. Sathyaprakash (**page 2129**) reviews the current and future status of observing gravitational waves, which bear the imprints of the earliest universe and also other strongly gravitating objects.

Soon after the field equations of general relativity were presented to the world, Schwarzschild found his famous blackhole solution. Atish Dabholkar (**page 2054**) traces the development of blackhole physics and the crucial role it is playing in discovering the quantum structure of gravity.

Contributions to condensed matter, optics and quantum mechanics

It was characteristic of Einstein that he mused about all basic physics problems of his time. In 1906 he applied the quantum hypothesis, outside of radiation theory, to calculate the specific heat of solids. This is the first paper on the quantum theory of the solid state. At the first Solvay conference in 1911, Einstein's concluding talk summarized, 'The current status of the problem of specific heats'. T. V. Ramakrishnan gives an account of the development of condensed matter physics and discusses the present status of some aspects of this vast area of physics (This contribution will appear in a later issue).

In 1916, after general relativity, he once again turned to radiation theory and statistical fluctuations. He discussed spontaneous and induced radiative processes. The concept of the photon as a particle with a quantum of energy and momentum was established in the same year. There is a gap of eleven years before Einstein associated a momentum $p = \frac{h\nu}{c}$ with the light quantum! The concept of the photon remained controversial until irrefutable evidence was provided by Compton's experiments in 1923.

In 1924 Bose's attempt to derive Planck's radiation law, using photons as indistinguishable particles, led to Bose–Einstein statistics for indistinguishable particles and the discovery of the phenomenon of Bose–Einstein condensation. Narendra Kumar (**page 2093**) writes about this contribution, and details modern experimental achievement of the new Bose–Einstein phase of matter and its impact on basic and condensed matter physics.

Even though Einstein was a pioneer of quantum theory and was the first to recognize that the new mechanics has a wave-particle duality, he was never convinced that the quantum mechanics formulated by Heisenberg, Schrödinger, Dirac and Born was a fundamental description of reality. The statistical interpretation of quantum mechanics greatly troubled him and he believed that a more fundamental theory underlying quantum mechanics had to be discovered. In 1935, with Podolsky and Rosen he came up with a thought experiment that reveals the conflict between locality and quantum entanglement. According to Einstein, 'No reasonable definition of reality can be permitted to do this'. However the present experimental verdict is not on Einstein's side. Virendra Singh (**page 2101**) discusses these developments.

Unified field theory

In the later years of his life, beginning around 1920, Einstein was mainly preoccupied with a quest for a unified theory of gravitation and electromagnetism. Even for the equations of general relativity, he had the following to say, '...it was essentially not anything more than a theory of the gravitational field, which was somewhat artificially isolated from a total field of yet unknown structure' (ref. 1, p. 75). He was appreciative of the work of Kaluza which achieved unification using a small fifth circular dimension, but (as usual) he pursued his own thoughts.

Einstein did not succeed in his unification program, but in the decades that followed this idea of a unified theory of all forces remained an inspiration and culminated in the unified theory of weak and electromagnetic interactions of Glashow, Weinberg and Salam in the 1970s. Unification of gravity with the weak, electromagnetic and strong forces is still one of the central themes in physics. David Gross, Michael Atiyah and Ashoke Sen (**page 2035, 2041, 2045**) trace these developments and describe the development of string theory as a framework for a unified theory. Abhay Ashtekar (**page 2064**) summarizes efforts to quantize gravity and also describes developments in loop quantum gravity.

Einstein's persona

During his lifetime Einstein was a public figure. He reached this stature by the sheer revolutionary nature of his science and his historic achievement. At the age of 37 years, he was the greatest scientist in the world. He was an active champion of peace, individual freedom and social justice. Unlike any other scientist of his generation he took strong and principled political positions. T. Jayaraman (**page 2141**) delineates Einstein's activism and involvement with social and political issues of his times.

Finally, in the words of Abraham Pais (ref. 2, p. 17), 'Einstein was the freest man I have known. He was a master of his own destiny. His deep sense of destiny led him farther than anyone before him. It was his faith in himself that made him persevere'.

1. *Albert Einstein: Philosopher Scientist* (ed. Schilpp, P. A.), Library of Living Philosophers, 1949, vol. 7.
2. Pais, A., *Subtle is the Lord: The Life and Science of Albert Einstein*, Oxford Univ. Press, 1982.

ACKNOWLEDGEMENTS. I thank all the authors for their enthusiastic response and for their excellent contributions, Leena Chandran-Wadia for a critical reading of the preface and Miriam Intrator of the Leo Baeck Institute, New York, for correspondence. The photos that appear in this issue are courtesy of the Leo Baeck Institute, the American Institute of Physics, the Institute for Advanced Study at Princeton and the Tata Institute of Fundamental Research, Mumbai. I thank these institutions for permission to reproduce them. Finally I thank the *Current Science* staff for their dedicated co-operation and efforts in preparing the Einstein special section.

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