ALBERT EINSTEIN

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Albert Einstein 14 March 1879 – 18 April 1955, was a German-born theoretical physicist who developed the theory of relativity, one of the two pillars of modern physics alongside quantum mechanics. His work is also known for its influence on the philosophy of science. He is best known by the general public for his mass–energy equivalence formula *E* = *mc*2 which has been dubbed “the world's most famous equation”. He received the 1921 Nobel Prize in Physics for his services to theoretical physics, and especially for his discovery of the law of the photoelectric effect, a pivotal step in the evolution of quantum theory.

Near the beginning of his career, Einstein thought that Newtonian mechanics was no longer enough to reconcile the laws of classical mechanics with the laws of the electromagnetic field. This led him to develop his special theory of relativity during his time at the Swiss Patent Office in Bern 1902–1909, Switzerland. However, he realized that the principle of relativity could also be extended to gravitational fields and—with his subsequent theory of gravitation in 1916—he published a paper on general relativity. He continued to deal with problems of statistical mechanics and quantum theory, which led to his explanations of particle theory and the motion of molecules. He also investigated the thermal properties of light which laid the foundation of the photon theory of light. In 1917, he applied the general theory of relativity to model the large-scale structure of the universe.

Between 1895 and 1914, he lived in Switzerland except for one year in Prague, 1911–12, where he received his academic diploma from the Swiss Federal Polytechnic in Zürich later the Eidgenössische Technische Hochschule, ETH in 1900. He later taught at that institute as a professor of theoretical physics between 1912 and 1914 before he left for Berlin. In 1901, after being stateless for more than five years, he acquired Swiss citizenship, which he kept for the rest of his life. In 1905, he was awarded a PhD by the University of Zürich. The same year, his *annus mirabilis* (miracle year), he published four groundbreaking papers, which were to bring him to the notice of the academic world, at the age of 26.

He was visiting the United States when Adolf Hitler came to power in 1933 and—being Jewish—did not go back to Germany, where he had been a professor at the Berlin Academy of Sciences. He settled in the United States, becoming an American citizen in 1940. On the eve of World War II, he endorsed a letter to President Franklin D. Roosevelt alerting him to the potential development of “extremely powerful bombs of a new type” and recommending that the U.S. begin similar research. This eventually led to what would become the Manhattan Project. Einstein supported defending the Allied forces, but generally denounced the idea of using the newly discovered nuclear fission as a weapon. Later, with the British philosopher Bertrand Russell, he signed the Russell–Einstein Manifesto, which highlighted the danger of nuclear weapons. He was affiliated with the Institute for Advanced Study in Princeton, New Jersey, until his death in 1955.

Einstein published more than 300 scientific papers along with over 150 non-scientific works. His intellectual achievements and originality have made the word “Einstein” synonymous with “genius”. Eugene Wigner wrote of Einstein in comparison to his contemporaries that “Einstein’s understanding was deeper even than Jansci von Neumann’s. His mind was both more penetrating and more original than von Neumann’s. And that is a very remarkable statement.”

Early life and education

Einstein's matriculation certificate at the age of 17, showing his final grades from the Argovian cantonal school (Aargauische Kantonsschule, on a scale of 1–6, with 6 being the highest possible mark). He scored: German 5; French 3; Italian 5; History 6; Geography 4; Algebra 6; Geometry 6; Descriptive Geometry 6; Physics 6; Chemistry 5; Natural History 5; Art and Technical Drawing 4.

Albert Einstein was born in Ulm, in the Kingdom of Württemberg in the German Empire, on 14 March 1879. His parents were Hermann Einstein, a salesman and engineer, and Pauline Koch. In 1880, the family moved to Munich, where Einstein's father and his uncle Jakob founded *Elektrotechnische Fabrik J. Einstein & Cie*, a company that manufactured electrical equipment based on direct current.

The Einsteins were non-observant Ashkenazi Jews and Albert attended a Catholic elementary school in Munich, from the age of 5, for three years. At the age of 8, he was transferred to the Luitpold Gymnasium, now known as the Albert Einstein Gymnasium, where he received advanced primary and secondary school education until he left the German Empire seven years later.

In 1894, Hermann and Jakob's company lost a bid to supply the city of Munich with electrical lighting because they lacked the capital to convert their equipment from the direct current (DC) standard to the more efficient alternating current (AC) standard. The loss forced the sale of the Munich factory. In search of business, the Einstein family moved to Italy, first to Milan and a few months later to Pavia. When the family moved to Pavia, Einstein, then 15, stayed in Munich to finish his studies at the Luitpold Gymnasium. His father intended for him to pursue electrical engineering, but Einstein clashed with authorities and resented the school’s regimen and teaching method. He later wrote that the spirit of learning and creative thought was lost in strict rote learning. At the end of December 1894, he travelled to Italy to join his family in Pavia, convincing the school to let him go by using a doctor’s note. During his time in Italy he wrote a short essay with the title “On the Investigation of the State of the Ether in a Magnetic Field”.

Einstein always excelled at math and physics from a young age, reaching some mathematical level years ahead of his peers. The twelve-year-old Einstein taught himself algebra and Euclidean geometry over a single summer. Einstein also independently discovered his own original proof of the Pythagorean theorem at age 12. A family tutor Max Talmud says that after he had given the 12-year-old Einstein a geometry textbook, after a short time “Einstein had worked through the whole book. He thereupon devoted himself to higher mathematics... Soon the flight of his mathematical genius was so high I could not follow.” His passion for geometry and algebra led the twelve-year-old to become convinced that nature could be understood as a "mathematical structure". Einstein started teaching himself calculus at 12, and as a 14-year-old he says he had “mastered integral and differential calculus”.

At age 13, Einstein was introduced to Kant's Critique of Pure Reason, and Kant became his favorite philosopher, his tutor stating: “At the time he was still a child, only thirteen years old, yet Kant's works, incomprehensible to ordinary mortals, seemed to be clear to him.”

In 1895, at the age of 16, Einstein took the entrance examinations for the Swiss Federal Polytechnic in Zürich, later the Eidgenössische Technische Hochschule, ETH. He failed to reach the required standard in the general part of the examination but obtained exceptional grades in physics and mathematics. On the advice of the principal of the Polytechnic, he attended the Argovian cantonal school (gymnasium) in Aarau, Switzerland, in 1895 and 1896 to complete his secondary schooling. While lodging with the family of professor Jost Winteler, he fell in love with Winteler’s daughter, Marie. Albert’s sister Maja later married Winteler’s son Paul. In January 1896, with his father’s approval, Einstein renounced his citizenship in the German Kingdom of Württemberg to avoid military service. In September 1896, he passed the Swiss Matura with mostly good grades, including a top grade of 6 in physics and mathematical subjects, on a scale of 1–6. At 17, he enrolled in the four-year mathematics and physics teaching diploma program at the Zürich Polytechnic. Marie Winteler, who was a year older, moved to Olsberg, Switzerland, for a teaching post.

Einstein’s future wife, a 20-year old Serbian woman Mileva Marić, also enrolled at the Polytechnic that year. She was the only woman among the six students in the mathematics and physics section of the teaching diploma course. Over the next few years, Einstein and Marić's friendship developed into romance, and they read books together on extra-curricular physics in which Einstein was taking an increasing interest. In 1900, Einstein passed the exams in Maths and Physics and was awarded the Federal Polytechnic teaching diploma. There have been claims that Marić collaborated with Einstein on his 1905 papers, known as the *Annus Mirabilis* papers, but historians of physics who have studied the issue find no evidence that she made any substantive contributions.

Scientific career

Throughout his life, Einstein published hundreds of books and articles. He published more than 300 scientific papers and 150 non-scientific ones. On 5 December 2014, universities and archives announced the release of Einstein’s papers, comprising more than 30,000 unique documents. Einstein’s intellectual achievements and originality have made the word “Einstein” synonymous with “genius”. In addition to the work he did by himself he also collaborated with other scientists on additional projects including the Bose–Einstein statistics, the Einstein refrigerator and others.

Statistical mechanics

Thermodynamic fluctuations and statistical physics

Einstein’s first paper submitted in 1900 to *Annalen der Physik* was on capillary attraction. It was published in 1901 with the title “Folgerungen aus den Capillaritätserscheinungen”, which translates as “Conclusions from the capillarity phenomena”. Two papers he published in 1902–1903 thermodynamics attempted to interpret atomic phenomena from a statistical point of view. These papers were the foundation for the 1905 paper on Brownian motion, which showed that Brownian movement can be construed as firm evidence that molecules exist. His research in 1903 and 1904 was mainly concerned with the effect of finite atomic size on diffusion phenomena.

Theory of critical opalescence

Einstein returned to the problem of thermodynamic fluctuations, giving a treatment of the density variations in a fluid at its critical point. Ordinarily the density fluctuations are controlled by the second derivative of the free energy with respect to the density. At the critical point, this derivative is zero, leading to large fluctuations. The effect of density fluctuations is that light of all wavelengths is scattered, making the fluid look milky white. Einstein relates this to Rayleigh scattering, which is what happens when the fluctuation size is much smaller than the wavelength, and which explains why the sky is blue. Einstein quantitatively derived critical opalescence from a treatment of density fluctuations and demonstrated how both the effect and Rayleigh scattering originate from the atomistic constitution of matter.

Special relativity

General principles

He articulated the principle of relativity. This was understood by Hermann Minkowski to be a generalization of rotational invariance from space to space-time. Other principles postulated by Einstein and later vindicated are the principle of equivalence, general covariance and the principle of adiabatic invariance of the quantum number.

Theory of relativity and *E* = *mc*²

Einstein’s “*Zur Elektrodynamik bewegter Körper”* (On the Electrodynamics of Moving Bodies) was received on 30 June 1905 and published 26 September of that same year. It reconciles Maxwell’s equations for electricity and magnetism with the laws of mechanics, by introducing major changes to mechanics close to the speed of light. This later became known as Einstein’s special theory of relativity.

Consequences of this include the time–space frame of a moving body appearing to slow down and contract in the direction of motion when measured in the frame of the observer. This paper also argued that the idea of a luminiferous ether—one of the leading theoretical entities in physics at the time—was superfluous.

In his paper on mass–energy equivalence, Einstein produced *E* = *mc*2 from his special relativity equations. Einstein’s 1905 work on relativity remained controversial for many years, but was accepted by leading physicists, starting with Max Planck.

General relativity

General relativity and the equivalence principle

General relativity is a theory of gravitation that was developed by Einstein between 1907 and 1915. According to general relativity, the observed gravitational attraction between masses results from the warping of space and time by those masses. General relativity has developed into an essential tool in modern astrophysics. It provides the foundation for the current understanding of black holes, regions of space where gravitational attraction is so strong that not even light can escape.

As Einstein later said, the reason for the development of general relativity was that the preference of inertial motions within special relativity was unsatisfactory, while a theory which from the outset prefers no state of motion, even accelerated ones, should appear more satisfactory. Consequently, in 1907 he published an article on acceleration under special relativity. In that article titled “On the Relativity Principle and the Conclusions Drawn from It”, he argued that free fall is really inertial motion, and that for a free-falling observer the rules of special relativity must apply. This argument is called the equivalence principle. In the same article, Einstein also predicted the phenomena of gravitational time dilation, gravitational red shift and deflection of light.

In 1911, Einstein published another article “On the Influence of Gravitation on the Propagation of Light” expanding on the 1907 article, in which he estimated the amount of deflection of light by massive bodies. Thus, the theoretical prediction of general relativity could for the first time be tested experimentally.

Gravitational waves

In 1916, Einstein predicted gravitational waves, ripples in the curvature of spacetime which propagate as waves, traveling outward from the source, transporting energy as gravitational radiation. The existence of gravitational waves is possible under general relativity due to its Lorentz invariance which brings the concept of a finite speed of propagation of the physical interactions of gravity with it. By contrast, gravitational waves cannot exist in the Newtonian theory of gravitation, which postulates that the physical interactions of gravity propagate at infinite speed.

The first, indirect, detection of gravitational waves came in the 1970s through observation of a pair of closely orbiting neutron stars, PSR B1913+16. The explanation of the decay in their orbital period was that they were emitting gravitational waves. Einstein's prediction was confirmed on 11 February 2016, when researchers at LIGO published the first observation of gravitational waves, on Earth, exactly one hundred years after the prediction.

Hole argument and Entwurf (Draft) theory

While developing general relativity, Einstein became confused about the gauge invariance in the theory. He formulated an argument that led him to conclude that a general relativistic field theory is impossible. He gave up looking for fully generally covariant tensor equations and searched for equations that would be invariant under general linear transformations only.

In June 1913, the Entwurf theory was the result of these investigations. As its name suggests, it was a sketch of a theory, less elegant and more difficult than general relativity, with the equations of motion supplemented by additional gauge fixing conditions. After more than two years of intensive work, Einstein realized that the hole argument was mistaken and abandoned the theory in November 1915.

Physical cosmology

In 1917, Einstein applied the general theory of relativity to the structure of the universe as a whole. He discovered that the general field equations predicted a universe that was dynamic, either contracting or expanding. As observational evidence for a dynamic universe was not known at the time, Einstein introduced a new term, the cosmological constant, to the field equations, in order to allow the theory to predict a static universe. The modified field equations predicted a static universe of closed curvature, in accordance with Einstein's understanding of Mach's principle in these years. This model became known as the Einstein World or Einstein's static universe.

Following the discovery of the recession of the nebulae by Edwin Hubble in 1929, Einstein abandoned his static model of the universe, and proposed two dynamic models of the cosmos, The Friedmann-Einstein universe of 1931 and the Einstein–de Sitter universe of 1932. In each of these models, Einstein discarded the cosmological constant, claiming that it was “in any case theoretically unsatisfactory”.

In many Einstein biographies, it is claimed that Einstein referred to the cosmological constant in later years as his “biggest blunder”. The astrophysicist Mario Livio has recently cast doubt on this claim, suggesting that it may be exaggerated.

In late 2013, a team led by the Irish physicist Cormac O’Raifeartaigh discovered evidence that, shortly after learning of Hubble’s observations of the recession of the nebulae, Einstein considered a steady-state model of the universe. In a hitherto overlooked manuscript, apparently written in early 1931, Einstein explored a model of the expanding universe in which the density of matter remains constant due to a continuous creation of matter, a process he associated with the cosmological constant. As he stated in the paper, “In what follows, I would like to draw attention to a solution to equation (1) that can account for Hubbel’s facts, and in which the density is constant over time”... If one considers a physically bounded volume, particles of matter will be continually leaving it. For the density to remain constant, new particles of matter must be continually formed in the volume from space.

It thus appears that Einstein considered a steady-state model of the expanding universe many years before Hoyle, Bondi and Gold. However, Einstein's steady-state model contained a fundamental flaw and he quickly abandoned the idea.

Energy momentum pseudo tensor

General relativity includes a dynamical spacetime, so it is difficult to see how to identify the conserved energy and momentum. Noether’s theorem allows these quantities to be determined from a Lagrangian with translation invariance, but general covariance makes translation invariance into something of a gauge symmetry. The energy and momentum derived within general relativity by Noether’s prescriptions do not make a real tensor for this reason.

Einstein argued that this is true for fundamental reasons, because the gravitational field could be made to vanish by a choice of coordinates. He maintained that the non-covariant energy momentum pseudo tensor was in fact the best description of the energy momentum distribution in a gravitational field. This approach has been echoed by Lev Landau and Evgeny Lifshitz, and others, and has become standard.

The use of non-covariant objects like pseudo tensors was heavily criticized in 1917 by Erwin Schrödinger and others.

Wormholes

In 1935, Einstein collaborated with Nathan Rosen to produce a model of a wormhole, often called Einstein–Rosen bridges. His motivation was to model elementary particles with charge as a solution of gravitational field equations, in line with the program outlined in the paper “Do Gravitational Fields play an Important Role in the Constitution of the Elementary Particles?”. These solutions cut and pasted Schwarzschild black holes to make a bridge between two patches.

If one end of a wormhole was positively charged, the other end would be negatively charged. These properties led Einstein to believe that pairs of particles and antiparticles could be described in this way.

Einstein–Cartan theory

In order to incorporate spinning point particles into general relativity, the affine connection needed to be generalized to include an antisymmetric part, called the torsion. This modification was made by Einstein and Cartan in the 1920s.

Equations of motion

The theory of general relativity has a fundamental law—the Einstein equations which describe how space curves, the geodesic equation which describes how particles move may be derived from the Einstein equations.

Since the equations of general relativity are non-linear, a lump of energy made out of pure gravitational fields, like a black hole, would move on a trajectory which is determined by the Einstein equations themselves, not by a new law. So, Einstein proposed that the path of a singular solution, like a black hole, would be determined to be a geodesic from general relativity itself.

This was established by Einstein, Infeld, and Hoffmann for point like objects without angular momentum, and by Roy Kerr for spinning objects.

Old quantum theory

The photoelectric effect. Incoming photons on the left strike a metal plate (bottom), and eject electrons, depicted as flying off to the right.

In a 1905 paper, Einstein postulated that light itself consists of localized particles (*quanta*). Einstein’s light quanta were nearly universally rejected by all physicists, including Max Planck and Niels Bohr. This idea only became universally accepted in 1919, with Robert Millikan's detailed experiments on the photoelectric effect, and with the measurement of Compton scattering.

Einstein concluded that each wave of frequency *f* is associated with a collection of photons with energy *hf* each, where *h* is Planck’s constant. He does not say much more, because he is not sure how the particles are related to the wave. But he does suggest that this idea would explain certain experimental results, notably the photoelectric effect.

Quantized atomic vibrations

In 1907, Einstein proposed a model of matter where each atom in a lattice structure is an independent harmonic oscillator. In the Einstein model, each atom oscillates independently—a series of equally spaced quantized states for each oscillator. Einstein was aware that getting the frequency of the actual oscillations would be difficult, but he nevertheless proposed this theory because it was a particularly clear demonstration that quantum mechanics could solve the specific heat problem in classical mechanics. Peter Debye refined this model.

Adiabatic principle and action-angle variables

Throughout the 1910s, quantum mechanics expanded in scope to cover many different systems. After Ernest Rutherford discovered the nucleus and proposed that electrons orbit like planets, Niels Bohr was able to show that the same quantum mechanical postulates introduced by Planck and developed by Einstein would explain the discrete motion of electrons in atoms, and the periodic table of the elements.

Einstein contributed to these developments by linking them with the 1898 arguments Wilhelm Wien had made. Wien had shown that the hypothesis of adiabatic invariance of a thermal equilibrium state allows all the blackbody curves at different temperature to be derived from one another by a simple shifting process. Einstein noted in 1911 that the same adiabatic principle shows that the quantity which is quantized in any mechanical motion must be an adiabatic invariant. Arnold Sommerfeld identified this adiabatic invariant as the action variable of classical mechanics.

Bose–Einstein statistics

In 1924, Einstein received a description of a statistical model from Indian physicist Satyendra Nath Bose, based on a counting method that assumed that light could be understood as a gas of indistinguishable particles. Einstein noted that Bose’s statistics applied to some atoms as well as to the proposed light particles and submitted his translation of Bose’s paper to the *Zeitschrift für Physik*. Einstein also published his own articles describing the model and its implications, among them the Bose–Einstein condensate phenomenon that some particulates should appear at very low temperatures. It was not until 1995 that the first such condensate was produced experimentally by Eric Allin Cornell and Carl Wieman using ultra-cooling equipment built at the NIST–JILA laboratory at the University of Colorado at Boulder. Bose–Einstein statistics are now used to describe the behaviors of any assembly of bosons. Einstein’s sketches for this project may be seen in the Einstein Archive in the library of the Leiden University.

Wave–particle duality

Einstein during his visit to the United States

Although the patent office promoted Einstein to Technical Examiner Second Class in 1906, he had not given up on academia. In 1908, he became a *Privatdozent* at the University of Bern. In “*Über die Entwicklung unserer Anschauungen über das Wesen und die Konstitution der Strahlung”* (The Development of our Views on the Composition and Essence of Radiation), on the quantization of light, and in an earlier 1909 paper, Einstein showed that Max Planck’s energy quanta must have well-defined momenta and act in some respects as independent, point-like particles. This paper introduced the *photon* concept, although the name *photon* was introduced later by Gilbert N. Lewis in 1926 and inspired the notion of wave–particle duality in quantum mechanics. Einstein saw this wave–particle duality in radiation as concrete evidence for his conviction that physics needed a new, unified foundation.

Zero-point energy

In a series of works completed from 1911 to 1913, Planck reformulated his 1900 quantum theory and introduced the idea of zero-point energy in his “second quantum theory”. Soon, this idea attracted the attention of Einstein and his assistant Otto Stern. Assuming the energy of rotating diatomic molecules contains zero-point energy, they then compared the theoretical specific heat of hydrogen gas with the experimental data. The numbers matched nicely. However, after publishing the findings, they promptly withdrew their support, because they no longer had confidence in the correctness of the idea of zero-point energy.

Stimulated emission

In 1917, at the height of his work on relativity, Einstein published an article in *Physikalische Zeitschrift* that proposed the possibility of stimulated emission, the physical process that makes possible the maser and the laser. This article showed that the statistics of absorption and emission of light would only be consistent with Planck’s distribution law if the emission of light into a mode with *n* photons would be enhanced statistically compared to the emission of light into an empty mode. This paper was enormously influential in the later development of quantum mechanics, because it was the first paper to show that the statistics of atomic transitions had simple laws.

Matter waves

Einstein discovered Louis de Broglie’s work and supported his ideas, which were received skeptically at first. In another major paper from this era, Einstein gave a wave equation for de Broglie waves, which Einstein suggested was the Hamilton–Jacobi equation of mechanics. This paper would inspire Schrödinger’s work of 1926.

Quantum mechanics

Einstein’s objections to quantum mechanics

Einstein was displeased with modern quantum mechanics as it had evolved after 1925. Contrary to popular belief, his doubts were not due to a conviction that God “is not playing at dice.” Indeed, it was Einstein himself, in his 1917 paper that proposed the possibility of stimulated emission, who first proposed the fundamental role of chance in explaining quantum processes. Rather, he objected to what quantum mechanics implies about the nature of reality. Einstein believed that a physical reality exists independent of our ability to observe it. In contrast, Bohr and his followers maintained that all we can know are the results of measurements and observations, and that it makes no sense to speculate about an ultimate reality that exists beyond our perceptions.

Bohr versus Einstein

The Bohr–Einstein debates were a series of public disputes about quantum mechanics between Einstein and Niels Bohr who were two of its founders. Their debates are remembered because of their importance to the philosophy of science. Their debates would influence later interpretations of quantum mechanics.

Einstein–Podolsky–Rosen (EPR) paradox

In 1935, Einstein returned to the question of quantum mechanics in the EPR paper. In a thought experiment, he considered two particles which had interacted such that their properties were strongly correlated. No matter how far the two particles were separated, a precise position measurement on one particle would result in equally precise knowledge of the position of the other particle; likewise, a precise momentum measurement of one particle would result in equally precise knowledge of the momentum of the other particle, without needing to disturb the other particle in any way.

Given Einstein’s concept of local realism, there were two possibilities: (1) either the other particle had these properties already determined, or (2) the process of measuring the first particle instantaneously affected the reality of the position and momentum of the second particle. Einstein rejected this second possibility popularly called “spooky action at a distance”.

This principle distilled the essence of Einstein’s objection to quantum mechanics. As a physical principle, it was shown to be incorrect when the Aspect experiment of 1982 confirmed Bell’s theorem, which J. S. Bell had delineated in 1964. The results of these and subsequent experiments demonstrate that quantum physics cannot be represented by any version of the classical picture of physics.

Although Einstein was wrong, his clear prediction of the unusual properties of *entangled quantum states* has resulted in the EPR paper becoming among the top ten papers published in Physical Review. It is considered a centerpiece of the development of quantum information theory.

Unified field theory

*Main article: Classical unified field theories*

Following his research on general relativity, Einstein entered into a series of attempts to generalize his geometric theory of gravitation to include electromagnetism as another aspect of a single entity. In 1950, he described his “unified field theory” in a *Scientific American* article titled “On the Generalized Theory of Gravitation”. Although he continued to be lauded for his work, Einstein became increasingly isolated in his research, and his efforts were ultimately unsuccessful. In his pursuit of a unification of the fundamental forces, Einstein ignored some mainstream developments in physics, most notably the strong and weak nuclear forces, which were not well understood until many years after his death. Mainstream physics, in turn, largely ignored Einstein’s approaches to unification. Einstein’s dream of unifying other laws of physics with gravity motivates modern quests for a theory of everything and in particular string theory, where geometrical fields emerge in a unified quantum-mechanical setting.