Albert Einstein

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Albert Einstein

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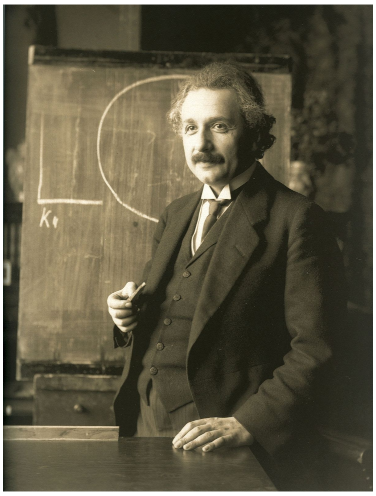


Albert Einstein in 1921

Born	14 March 1879 Ulm, Kingdom of Württemberg, German Empire
Died	18 April 1955 (aged 76) Princeton, New Jersey, U.S.
Residence	Germany, Italy, Switzerland, Austria, Belgium, United States
Citizenship	• Kingdom of Württemberg (1879–1896) • Stateless (1896–1901) • Switzerland (1901–1955) • Austria–Hungary (1911–1912) • German Empire (1914–1918) • Weimar Republic (1919-March 1933) • United States (1940–1955)
Fields	Physics
Institutions	• Swiss Patent Office (Bern) • University of Zurich • Charles University in Prague • ETH Zurich • Caltech • Prussian Academy of Sciences • Kaiser Wilhelm Institute • University of Leiden • Institute for Advanced Study
Alma mater	• ETH Zurich • University of Zurich
Doctoral advisor	Alfred Kleiner

Other academic advisors	Heinrich Friedrich Weber
Notable students	• Ernst G. Straus • Nathan Rosen • Leó Szilárd • Raziuddin Siddiqui[1]
Known for	• General relativity and special relativity • Photoelectric effect • Mass-energy equivalence • Theory of Brownian Motion • Einstein field equations • Bose–Einstein statistics • Bose-Einstein condensate • Bose–Einstein correlations • Unified Field Theory • EPR paradox
Notable awards	• Nobel Prize in Physics (1921) • Matteucci Medal (1921) • Copley Medal (1925) • Max Planck Medal (1929) • *Time* Person of the Century (1999)
Spouse	Mileva Marić (1903–1919) Elsa Löwenthal (1919–1936)
Children	Lieserl (1902-1903?) Hans Albert (1904-1973) Eduard "Tete" (1910-1965)
Signature	Albert Einstein

Albert Einstein (/ˈælbərtHelp:IPA for English#Keyˈaɪnstaɪn/; German: [ˈalbɐt ˈaɪnʃtaɪn] (🔊 listen); 14 March 1879 – 18 April 1955) was a German-born theoretical physicist who developed the general theory of relativity, one of the two pillars of modern physics (alongside quantum mechanics).[2][3] While best known for his mass–energy equivalence formula $E = mc^2$ (which has been dubbed "the world's most famous equation"),[4] 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".[5] The latter was pivotal in establishing 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 to the development of his special theory of relativity. He realized, however, 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 the general theory of 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, Einstein applied the general theory of relativity to model the large-scale structure of the universe.[6]

He was visiting the United States when Adolf Hitler came to power in 1933 and did not go back to Germany, where he had been a professor at the Berlin Academy of Sciences. He settled in the U.S., becoming an American citizen in 1940.[] On the eve of World War II, he helped alert President Franklin D. Roosevelt that Germany might be developing an atomic weapon and recommended that the U.S. begin similar research; this eventually led to what would become the Manhattan Project. Einstein was in support of defending the Allied forces, but largely denounced using the new discovery of nuclear fission as a weapon. Later, with the British philosopher Bertrand Russell, Einstein signed the Russell–Einstein Manifesto, which highlighted the danger of nuclear weapons. Einstein 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.[6][7] His great intellectual achievements and originality have made the word "Einstein" synonymous with genius.[8]

Biography

Early life and education

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

Einstein at the age of three in 1882

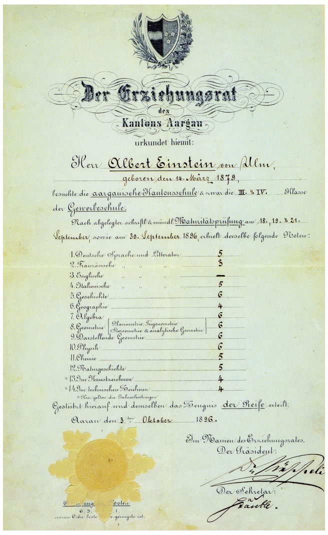
The Einsteins were non-observant Jews. Albert attended a Catholic elementary school from the age of five for three years. At the age of eight, he was transferred to the Luitpold Gymnasium (now known as the Albert Einstein Gymnasium) where he received advanced primary and secondary school education until he left Germany seven years later.[] Contrary to popular suggestions that he had struggled with early speech difficulties, the Albert Einstein Archives indicate he excelled at the first school that he attended.[] He was right-handed;[][9] there appears to be no evidence for the widespread popular belief[10] that he was left-handed.

Albert Einstein in 1893 (age 14)

His father once showed him a pocket compass; Einstein realized that there must be something causing the needle to move, despite the apparent "empty space".[11] As he grew, Einstein built models and mechanical devices for fun and began to show a talent for mathematics.[] When Einstein was ten years old, Max Talmud (later changed to Max Talmey), a poor Jewish medical student from Poland, was introduced to the Einstein family by his brother. During weekly visits over the next five years, he gave the boy popular books on science, mathematical texts and philosophical writings. These included Immanuel Kant's *Critique of Pure Reason*, and *Euclid's Elements* (which Einstein called the "holy little geometry book").[12][13][14]</ref>

In 1894, his father's company failed: direct current (DC) lost the War of Currents to alternating current (AC). In search of business, the Einstein family moved to Italy, first to Milan and then, a few months later, to Pavia. When the family moved to Pavia, Einstein 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 were 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.[15] It was during his time in Italy that he wrote a short essay with the title "On the Investigation of the State of the Ether in a Magnetic Field."[16][17]

In 1895, at the age of sixteen, Einstein sat the entrance examinations for the Swiss Federal Polytechnic in Zurich (later the Eidgenössische Polytechnische Schule). He failed to reach the required standard in several subjects, but obtained exceptional grades in physics and mathematics.[18] On the advice of the Principal of the Polytechnic, he attended the Aargau Cantonal School in Aarau, Switzerland, in 1895–96 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 Wintelers' son Paul.)[19] In January 1896, with his father's approval, he renounced his citizenship in the German Kingdom of Württemberg to avoid military service.[20] (He acquired Swiss citizenship five years later, in February 1901.)[21] 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),[22] and, though only seventeen, enrolled in the four-year mathematics and physics teaching diploma program at the ETH Zurich. Marie Winteler moved to Olsberg, Switzerland for a teaching post.



Der Erziehungsrat
des
Kantons Aargau
urkundet hiemit:

Herr Albert Einstein von Ulm,
geboren den 14. März 1879,
besuchte die aargauische Kantonsschule & zwar die III. & IV. Klasse
der Gewerbeschule.

Nach abgelegter schriftl. & mündl. Maturitätsprüfung am 18., 19. & 21. September, sowie am 30. September 1896 erhielt derselbe folgende Noten:

1. Deutsche Sprache und Litteratur	5
2. Französische " " "	3
3. Englische " " "	—
4. Italienische " " "	5
5. Geschichte	6
6. Geographie	4
7. Algebra	6
8. Geometrie (Planimetrie, Trigonometrie, Stereometrie & analytische Geometrie)	6
9. Darstellende Geometrie	6
10. Physik	6
11. Chemie	5
12. Naturgeschichte	5
* 13. Im Kunstzeichnen	4
* 14. Im technischen Zeichnen	4

* Hier gelten die Jahresleistungen.

Gestützt hierauf wird demselben das Zeugnis der Reife erteilt.

Aarau den 3ten Oktober 1896.

Im Namen des Erziehungsrates,
Der Präsident:
Dr. Käppeli
Der Sekretär:
Stäuble.

[illegible] Noten
6, 5, [illegible] 1,
wovon 6 die beste [illegible] geringste ist.

Einstein's matriculation certificate at the age of 17, showing his final grades from the Aargau Kantonsschule (on a scale of 1-6, with 6 being the best mark).

Einstein's future wife, Mileva Marić, also enrolled at the Polytechnic that same year, 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 was awarded the Zurich Polytechnic teaching diploma, but Marić failed the examination with a poor grade in the mathematics component, theory of functions.[23] There have been claims that Marić collaborated with Einstein on his celebrated 1905 papers,[24][25] but historians of physics who have studied the issue find no evidence that she made any substantive contributions.[26][27][28][29]

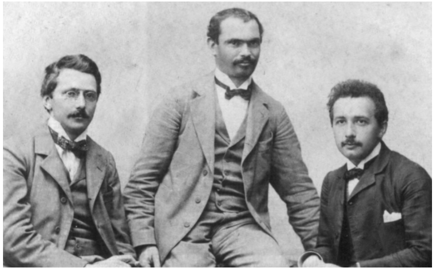
Marriages and children

In early 1902, Einstein and Marić had a daughter they named Lieserl, born in Novi Sad where Marić was staying with her parents. Her fate is unknown, but the contents of a letter Einstein wrote to Marić in September 1903 suggest that she was either adopted or died of scarlet fever in infancy.[30][31]

Einstein and Marić married in January 1903. In May 1904, the couple's first son, Hans Albert Einstein, was born in Bern, Switzerland. Their second son, Eduard, was born in Zurich in July 1910. In 1914, Einstein moved to Berlin, while his wife remained in Zurich with their sons. They divorced on 14 February 1919, having lived apart for five years.

Einstein married Elsa Löwenthal on 2 June 1919, after having had a relationship with her since 1912. She was his first cousin maternally and his second cousin paternally. In 1933, they emigrated to the United States. In 1935, Elsa Einstein was diagnosed with heart and kidney problems and died in December 1936.[]

Patent office

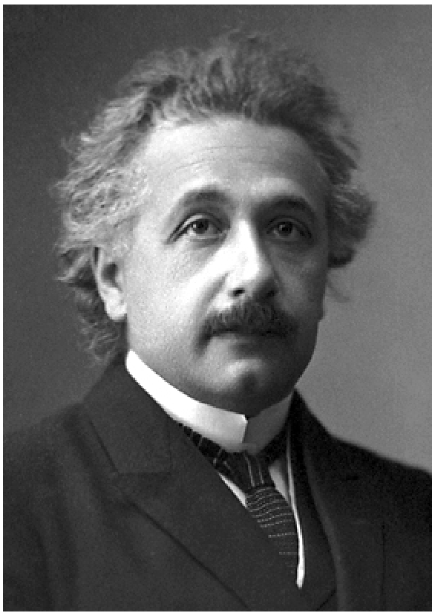

Left to right: Conrad Habicht, Maurice Solovine and Einstein, who founded the Olympia Academy

After graduating, Einstein spent almost two frustrating years searching for a teaching post, but Marcel Grossmann's father helped him secure a job in Bern,[32] at the Federal Office for Intellectual Property, the patent office, as an assistant examiner.[33] He evaluated patent applications for electromagnetic devices. In 1903, Einstein's position at the Swiss Patent Office became permanent, although he was passed over for promotion until he "fully mastered machine technology".[34]

Much of his work at the patent office related to questions about transmission of electric signals and electrical-mechanical synchronization of time, two technical problems that show up conspicuously in the thought experiments that eventually led Einstein to his radical conclusions about the nature of light and the fundamental connection between space and time.[35]

With a few friends he met in Bern, Einstein started a small discussion group, self-mockingly named "The Olympia Academy", which met regularly to discuss science and philosophy. Their readings included the works of Henri Poincaré, Ernst Mach, and David Hume, which influenced his scientific and philosophical outlook.

Academic career


Einstein's official 1921 portrait after receiving the Nobel Prize in Physics.

In 1901, his paper "Folgerungen aus den Capillaritätserscheinungen" ("Conclusions from the Capillarity Phenomena") was published in the prestigious *Annalen der Physik*.[36][37] On 30 April 1905, Einstein completed his thesis, with Alfred Kleiner, Professor of Experimental Physics, serving as *pro-forma* advisor. Einstein was awarded a PhD by the University of Zurich. His dissertation was entitled "A New Determination of Molecular Dimensions".[38][39] That same year, which has been called Einstein's *annus mirabilis* (miracle year), he published four groundbreaking papers, on the photoelectric effect, Brownian motion, special relativity, and the equivalence of mass and energy, which were to bring him to the notice of the academic world.

By 1908, he was recognized as a leading scientist, and he was appointed lecturer at the University of Bern. The following year, he quit the patent office and the lectureship to take the position of physics docent[40] at the University of Zurich. He became a full professor at Karl-Ferdinand University in Prague in 1911. In 1914, he returned to Germany after being appointed director of the Kaiser Wilhelm Institute for Physics (1914–1932)[41] and a professor at the Humboldt University of Berlin, with a special clause in his contract that freed him from most teaching obligations. He became a member of the Prussian Academy of Sciences. In 1916, Einstein was appointed president of the German Physical Society (1916–1918).[42][43]

During 1911, he had calculated that, based on his new theory of general relativity, light from another star would be bent by the Sun's gravity. That prediction was claimed confirmed by observations made by a British expedition led by Sir Arthur Eddington during the solar eclipse of 29 May 1919. International media reports of this made Einstein world famous. On 7 November 1919, the leading British newspaper *The Times* printed a banner headline that read: "Revolution in Science – New Theory of the Universe – Newtonian Ideas Overthrown".[] Much later, questions were raised whether the measurements had been accurate enough to support Einstein's theory. In 1980 historians John

Earman and Clark Glymour published an analysis suggesting that Eddington had suppressed unfavorable results.[44] The two reviewers found possible flaws in Eddington's selection of data, but their doubts, although widely quoted and, indeed, now with a "mythical" status almost equivalent to the status of the original observations, have not been confirmed.[45][46] Eddington's selection from the data seems valid and his team indeed made astronomical measurements verifying the theory.[47]

In 1921, Einstein was awarded the Nobel Prize in Physics for his explanation of the photoelectric effect, as relativity was considered still somewhat controversial. He also received the Copley Medal from the Royal Society in 1925.

Travels abroad

Einstein visited New York City for the first time on 2 April 1921, where he received an official welcome by Mayor Hylan, followed by three weeks of lectures and receptions. He went on to deliver several lectures at Columbia University and Princeton University, and in Washington he accompanied representatives of the National Academy of Science on a visit to the White House. On his return to Europe he was the guest of the British statesman and philosopher Viscount Haldane in London, where he met several renowned scientific, intellectual and political figures, and delivered a lecture at King's College.[48]

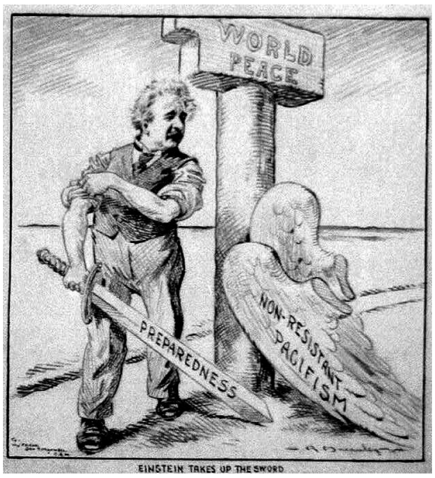
Einstein in N.Y., 1921, his first visit to U.S.

In 1922, he traveled throughout Asia and later to Palestine, as part of a six-month excursion and speaking tour. His travels included Singapore, Ceylon, and Japan, where he gave a series of lectures to thousands of Japanese. His first lecture in Tokyo lasted four hours, after which he met the emperor and empress at the Imperial Palace where thousands came to watch. Einstein later gave his impressions of the Japanese in a letter to his sons:[49]:307 "Of all the people I have met, I like the Japanese most, as they are modest, intelligent, considerate, and have a feel for art."[49]:308

On his return voyage, he also visited Palestine for 12 days in what would become his only visit to that region. "He was greeted with great British pomp, as if he were a head of state rather than a theoretical physicist", writes Isaacson. This included a cannon salute upon his arrival at the residence of the British high commissioner, Sir Herbert Samuel. During one reception given to him, the building was "stormed by throngs who wanted to hear him". In Einstein's talk to the audience, he expressed his happiness over the event:

> I consider this the greatest day of my life. Before, I have always found something to regret in the Jewish soul, and that is the forgetfulness of its own people. Today, I have been made happy by the sight of the Jewish people learning to recognize themselves and to make themselves recognized as a force in the world.[50]:308

Emigration to U.S. in 1933

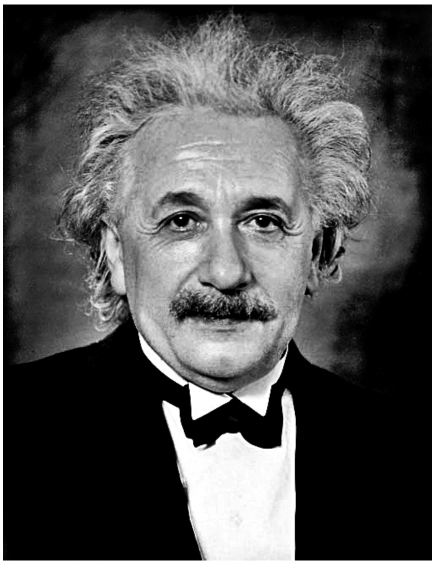


Cartoon of Einstein, who has shed his "Pacifism" wings, standing next to a pillar labeled "World Peace." He is rolling up his sleeves and holding a sword labeled "Preparedness" (circa 1933).

In February 1933 while on a visit to the United States, Einstein decided not to return to Germany due to the rise to power of the Nazis under Germany's new chancellor.[51][52] He visited American universities in early 1933 where he undertook his third two-month visiting professorship at the California Institute of Technology in Pasadena. He and his wife Elsa returned by ship to Belgium at the end of March. During the voyage they were informed that their cottage was raided by the Nazis and his personal sailboat had been confiscated. Upon landing in Antwerp on 28 March, he immediately went to the German consulate where he turned in his passport and formally renounced his German citizenship.[50]

In early April, he learned that the new German government had passed laws barring Jews from holding any official positions, including teaching at universities.[50] A month later, Einstein's works were among those targeted by Nazi book burnings, and Nazi propaganda minister Joseph Goebbels proclaimed, "Jewish intellectualism is dead."[50] Einstein also learned that his name was on a list of assassination targets, with a "$5,000 bounty on his head."[50] One German magazine included him in a list of enemies of the German regime with the phrase, "not yet hanged".[50]

He resided in Belgium for some months, before temporarily living in England.[53][54] In a letter to his friend, physicist Max Born, who also emigrated from Germany and lived in England, Einstein wrote, "... I must confess that the degree of their brutality and cowardice came as something of a surprise."[50]



Portrait taken in 1935 at Princeton

In October 1933 he returned to the U.S. and took up a position at the Institute for Advanced Study at Princeton, New Jersey, that required his presence for six months each year.[55][56] He was still undecided on his future (he had offers from European universities, including Oxford), but in 1935 he arrived at the decision to remain permanently in the United States and apply for citizenship.[57][58]

His affiliation with the Institute for Advanced Study would last until his death in 1955.[59] He was one of the four first selected (two of the others being John von Neumann and Kurt Gödel) at the new Institute, where he soon developed a close friendship with Gödel. The two would take long walks together discussing their work. His last assistant was Bruria Kaufman, who later became a physicist. During this period, Einstein tried to develop a unified field theory and to refute the accepted interpretation of quantum physics, both unsuccessfully.

Other scientists also fled to America. Among them were Nobel laureates and professors of theoretical physics. With so many other Jewish scientists now forced by circumstances to live in America, often working side by side, Einstein wrote to a friend, "For me the most beautiful thing is to be in contact with a few fine Jews—a few millennia of a civilized past do mean something after all." In another letter he writes, "In my whole life I have never felt so Jewish as now."[50]

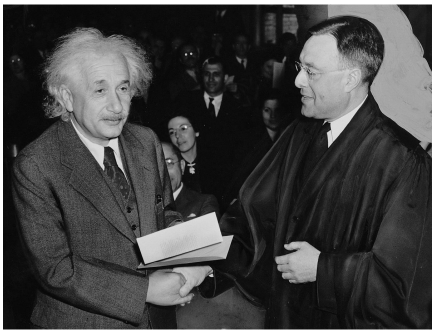
World War II and the Manhattan Project

In 1939, a group of Hungarian scientists that included emigre physicist Leó Szilárd attempted to alert Washington of ongoing Nazi atomic bomb research. The group's warnings were discounted.[] Einstein and Szilárd, along with other refugees such as Edward Teller and Eugene Wigner, "regarded it as their responsibility to alert Americans to the possibility that German scientists might win the race to build an atomic bomb, and to warn that Hitler would be more than willing to resort to such a weapon."[49]:630[60] In the summer of 1939, a few months before the beginning of World War II in Europe, Einstein was persuaded to lend his prestige by writing a letter with Szilárd to President Franklin D. Roosevelt to alert him of the possibility. The letter also recommended that the U.S. government pay attention to and become directly involved in uranium research and associated chain reaction research.

The letter is believed to be "arguably the key stimulus for the U.S. adoption of serious investigations into nuclear weapons on the eve of the U.S. entry into World War II".[61] President Roosevelt could not take the risk of allowing Hitler to possess atomic bombs first. As a result of Einstein's letter and his meetings with Roosevelt, the U.S. entered the "race" to develop the bomb, drawing on its "immense material, financial, and scientific resources" to initiate the Manhattan Project. It became the only country to successfully develop an atomic bomb during World War II.

For Einstein, "war was a disease ... [and] he called for resistance to war." But in 1933, after Hitler assumed full power in Germany, "he renounced pacifism altogether ... In fact, he urged the Western powers to prepare themselves against another German onslaught."[62]:110 In 1954, a year before his death, Einstein said to his old friend, Linus Pauling, "I made one great mistake in my life — when I signed the letter to President Roosevelt recommending that atom bombs be made; but there was some justification — the danger that the Germans would make them ..."[63]

U.S. citizenship

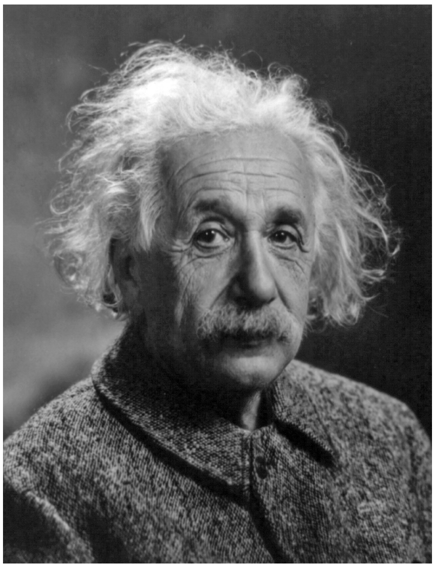


Einstein accepting U.S. citizenship certificate from judge Phillip Forman

Einstein became an American citizen in 1940. Not long after settling into his career at Princeton, he expressed his appreciation of the "meritocracy" in American culture when compared to Europe. According to Isaacson, he recognized the "right of individuals to say and think what they pleased", without social barriers, and as result, the individual was "encouraged" to be more creative, a trait he valued from his own early education. Einstein writes:

> What makes the new arrival devoted to this country is the democratic trait among the people. No one humbles himself before another person or class ... American youth has the good fortune not to have its outlook troubled by outworn traditions.[50]:432

As a member of the National Association for the Advancement of Colored People (NAACP) at Princeton who campaigned for the civil rights of African Americans, Einstein corresponded with civil rights activist W. E. B. Du Bois, and in 1946 Einstein called racism America's "worst disease".[64] He later stated, "Race prejudice has unfortunately become an American tradition which is uncritically handed down from one generation to the next. The only remedies are enlightenment and education".[65]



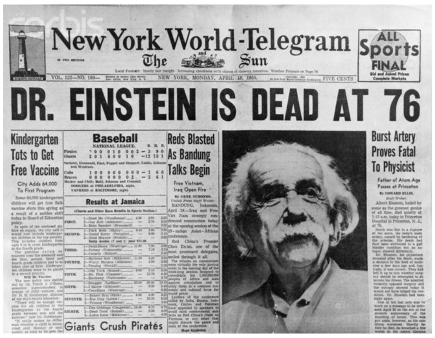
Einstein in 1947

During the final stage of his life, Einstein transitioned to a vegetarian lifestyle,[66] arguing that "the vegetarian manner of living by its purely physical effect on the human temperament would most beneficially influence the lot of mankind".[67]

After the death of Israel's first president, Chaim Weizmann, in November 1952, Prime Minister David Ben-Gurion offered Einstein the position of President of Israel, a mostly ceremonial post.[] The offer was presented by Israel's ambassador in Washington, Abba Eban, who explained that the offer "embodies the deepest respect which the Jewish people can repose in any of its sons".[49]:522 However, Einstein declined, and wrote in his response that he was "deeply moved", and "at once saddened and ashamed" that he could not accept it:

> All my life I have dealt with objective matters, hence I lack both the natural aptitude and the experience to deal properly with people and to exercise official function. I am the more distressed over these circumstances because my relationship with the Jewish people became my strongest human tie once I achieved complete clarity about our precarious position among the nations of the world.[49]:*522*[][68]

Death



New York World-Telegram
The Sun
ALL Sports FINAL
NEW YORK, MONDAY, APRIL 18, 1955.
FIVE CENTS

DR. EINSTEIN IS DEAD AT 76

Kindergarten Tots to Get Free Vaccine

Baseball

Reds Blasted As Bandung Talks Begin

Burst Artery Proves Fatal To Physicist

Giants Crush Pirates

The *New York World-Telegram* announces Einstein's death on 18 April 1955.

On 17 April 1955, Albert Einstein experienced internal bleeding caused by the rupture of an abdominal aortic aneurysm, which had previously been reinforced surgically by Dr. Rudolph Nissen in 1948.[69] He took the draft of a speech he was preparing for a television appearance commemorating the State of Israel's seventh anniversary with him to the hospital, but he did not live long enough to complete it.[70] Einstein refused surgery, saying: "I want to go when I want. It is tasteless to prolong life artificially. I have done my share, it is time to go. I will do it elegantly."[71] He died in Princeton Hospital early the next morning at the age of 76, having continued to work until near the end.

During the autopsy, the pathologist of Princeton Hospital, Thomas Stoltz Harvey, removed Einstein's brain for preservation without the permission of his family, in the hope that the neuroscience of the future would be able to discover what made Einstein so intelligent.[72] Einstein's remains were cremated and his ashes were scattered at an undisclosed location.[73][74]

In his lecture at Einstein's memorial, nuclear physicist Robert Oppenheimer summarized his impression of him as a person: "He was almost wholly without sophistication and wholly without worldliness ... There was always with him a wonderful purity at once childlike and profoundly stubborn."[62]

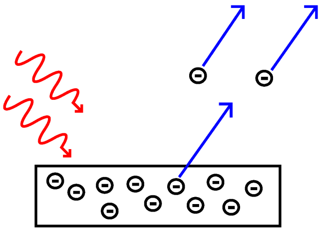
Scientific career

Throughout his life, Einstein published hundreds of books and articles.[7][] 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.[75]

Albert Einstein in 1904

1905 – Annus Mirabilis papers

The *Annus Mirabilis* papers are four articles pertaining to the photoelectric effect (which gave rise to quantum theory), Brownian motion, the special theory of relativity, and E = mc^2 that Albert Einstein published in the *Annalen der Physik* scientific journal in 1905. These four works contributed substantially to the foundation of modern physics and changed views on space, time, and matter. The four papers are:



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

Title (translated)	Area of focus	Received	Published	Significance
On a Heuristic Viewpoint Concerning the Production and Transformation of Light	Photoelectric effect	18 March	9 June	Resolved an unsolved puzzle by suggesting that energy is exchanged only in discrete amounts (quanta).[76] This idea was pivotal to the early development of quantum theory.[77]
On the Motion of Small Particles Suspended in a Stationary Liquid, as Required by the Molecular Kinetic Theory of Heat	Brownian motion	11 May	18 July	Explained empirical evidence for the atomic theory, supporting the application of statistical physics.
On the Electrodynamics of Moving Bodies	Special relativity	30 June	26 September	Reconciled Maxwell's equations for electricity and magnetism with the laws of mechanics by introducing major changes to mechanics close to the speed of light, resulting from analysis based on empirical evidence that the speed of light is independent of the motion of the observer.[78] Discredited the concept of a "luminiferous ether."[79]
Does the Inertia of a Body Depend Upon Its Energy Content?	Matter–energy equivalence	27 September	21 November	Equivalence of matter and energy, $E = mc^2$ (and by implication, the ability of gravity to "bend" light), the existence of "rest energy", and the basis of nuclear energy.

Thermodynamic fluctuations and statistical physics

Albert 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 Kapillarität Erscheinungen," 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.[]

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 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 aether – one of the leading theoretical entities in physics at the time – was superfluous.[80]

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.[81][82]

Photons and energy quanta

In a 1905 paper,[83] 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.[84]

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 different, 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.[85]

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. The law that the action variable is quantized was a basic principle of the quantum theory as it was known between 1900 and 1925.[*citation needed*]

Wave–particle duality

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.[86] 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 during his visit to the United States

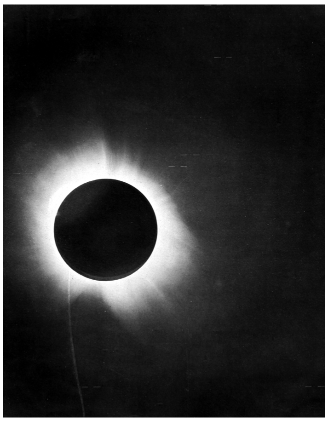
Theory of critical opalescence

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 Raleigh scattering, which is what happens when the fluctuation size is much smaller than the wavelength, and which explains why the sky is blue.[87] 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.

Zero-point energy

Einstein's physical intuition led him to note that Planck's oscillator energies had an incorrect zero point. He modified Planck's hypothesis by stating that the lowest energy state of an oscillator is equal to $^1/_2hf$, to half the energy spacing between levels. This argument, which was made in 1913 in collaboration with Otto Stern, was based on the thermodynamics of a diatomic molecule which can split apart into two free atoms.

General relativity and the equivalence principle



Eddington's photograph of a solar eclipse.

General relativity (GR) is a theory of gravitation that was developed by Albert 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 Albert 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.[88] So in 1908 he published an article on acceleration under special relativity. In that article, he argued that free fall is really inertial motion, and that for a freefalling observer the rules of special relativity must apply. This argument is called the Equivalence principle. In the same article, Einstein also predicted the phenomenon of gravitational time dilation. In 1911, Einstein published another article expanding on the 1907 article, in which additional effects such as the deflection of light by massive bodies were predicted.

Hole argument and Entwurf theory

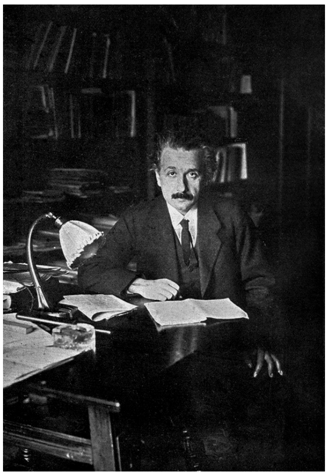
While developing general relativity, Einstein became confused about the gauge invariance in the theory. He formulated an argument that led him to conclude that a general relativistic field theory is impossible. He gave up looking for fully generally covariant tensor equations, and searched for equations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

In June 1913 the Entwurf ("draft") theory was the result of these investigations. As its name suggests, it was a sketch of a theory, with the equations of motion supplemented by additional gauge fixing conditions. Simultaneously less elegant and more difficult than general relativity, after more than two years of intensive work Einstein abandoned the theory in November 1915 after realizing that the hole argument was mistaken.[89]

Cosmology

In 1917, Einstein applied the General theory of relativity to model the structure of the universe as a whole. He wanted the universe to be eternal and unchanging, but this type of universe is not consistent with relativity. To fix this, Einstein modified the general theory by introducing a new notion, the cosmological constant. With a positive cosmological constant, the universe could be an eternal static sphere.[90]

Einstein believed a spherical static universe is philosophically preferred, because it would obey Mach's principle. He had shown that general relativity incorporates Mach's principle to a certain extent in frame dragging by gravitomagnetic fields, but he knew that Mach's idea would not work if space goes on forever. In a closed universe, he believed that Mach's principle would hold. Mach's principle has generated much controversy over the years.


Einstein in his office at the University of Berlin.

Modern quantum theory

Einstein was displeased with quantum theory and mechanics, despite its acceptance by other physicists, stating "God doesn't play with dice." As Einstein died at the age of 76 he still would not accept quantum theory.[91] 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.[92] 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. 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.

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.[93] 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.[94] 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.[]

Energy momentum pseudotensor

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 presecriptions 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 pseudotensor 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 pseudotensors was heavily criticized in 1917 by Erwin Schrödinger and others.

Unified field theory

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 entitled "On the Generalized Theory of Gravitation".[95] 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.

Wormholes

Einstein collaborated with others to produce a model of a wormhole. 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.

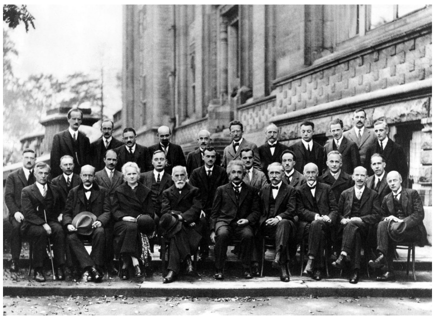
This was established by Einstein, Infeld, and Hoffmann for pointlike objects without angular momentum, and by Roy Kerr for spinning objects.

Other investigations

Einstein conducted other investigations that were unsuccessful and abandoned. These pertain to force, superconductivity, gravitational waves, and other research. Please see the main article for details.

Collaboration with other scientists

In addition to longtime collaborators Leopold Infeld, Nathan Rosen, Peter Bergmann and others, Einstein also had some one-shot collaborations with various scientists.


The 1927 Solvay Conference in Brussels, a gathering of the world's top physicists. Einstein in the center.

Einstein–de Haas experiment

Einstein and De Haas demonstrated that magnetization is due to the motion of electrons, nowadays known to be the spin. In order to show this, they reversed the magnetization in an iron bar suspended on a torsion pendulum. They confirmed that this leads the bar to rotate, because the electron's angular momentum changes as the magnetization changes. This experiment needed to be sensitive, because the angular momentum associated with electrons is small, but it definitively established that electron motion of some kind is responsible for magnetization.

Schrödinger gas model

Einstein suggested to Erwin Schrödinger that he might be able to reproduce the statistics of a Bose–Einstein gas by considering a box. Then to each possible quantum motion of a particle in a box associate an independent harmonic oscillator. Quantizing these oscillators, each level will have an integer occupation number, which will be the number of particles in it.

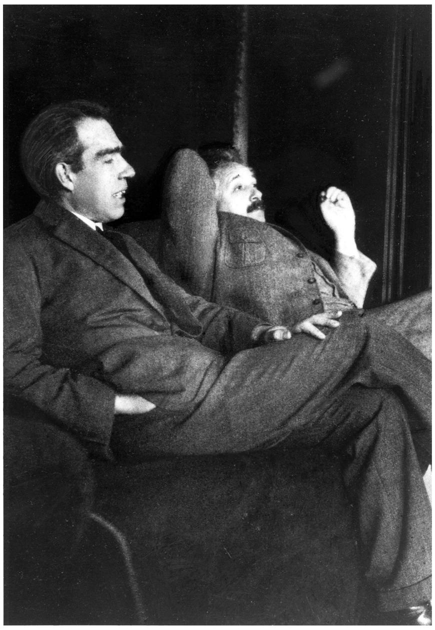
This formulation is a form of second quantization, but it predates modern quantum mechanics. Erwin Schrödinger applied this to derive the thermodynamic properties of a semiclassical ideal gas. Schrödinger urged Einstein to add his name as co-author, although Einstein declined the invitation.[96]

Einstein refrigerator

In 1926, Einstein and his former student Leó Szilárd co-invented (and in 1930, patented) the Einstein refrigerator. This absorption refrigerator was then revolutionary for having no moving parts and using only heat as an input.[97] On 11 November 1930, U.S. Patent 1,781,541 [98] was awarded to Albert Einstein and Leó Szilárd for the refrigerator. Their invention was not immediately put into commercial production, as the most promising of their patents were quickly bought up by the Swedish company Electrolux to protect its refrigeration technology from competition.[99]

Bohr versus Einstein

The Bohr–Einstein debates were a series of public disputes about quantum mechanics between Albert Einstein and Niels Bohr who were two of its founders. Their debates are remembered because of their importance to the philosophy of science.[100][101][102]


Einstein and Niels Bohr, 1925

Einstein–Podolsky–Rosen paradox

In 1935, Einstein returned to the question of quantum mechanics. He considered how a measurement on one of two entangled particles would affect the other. He noted, along with his collaborators, that by performing different measurements on the distant particle, either of position or momentum, different properties of the entangled partner could be discovered without disturbing it in any way.

He then used a hypothesis of local realism to conclude that the other particle had these properties already determined. The principle he proposed is that if it is possible to determine what the answer to a position or momentum measurement would be, without in any way disturbing the particle, then the particle actually has values of position or momentum.

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 had been promulgated in 1964.

Political and religious views


Albert Einstein, seen here with his wife Elsa Einstein and Zionist leaders, including future President of Israel Chaim Weizmann, his wife Vera Weizmann, Menahem Ussishkin, and Ben-Zion Mossinson on arrival in New York City in 1921.

Einstein's political view was in favor of socialism and critical of capitalism, which he detailed in essays like "Why Socialism?";[103][104] his political views emerged publicly in the middle of the 20th century due to his fame and reputation for genius. Einstein offered to and was called on to give judgments and opinions on matters often unrelated to theoretical physics or mathematics.[105]

Einstein's views about religious belief have been collected from interviews and original writings. He said he believed in the "pantheistic" God of Baruch Spinoza, but not in a personal god, a belief he criticized. He called himself an agnostic, while disassociating himself from the label atheist.[106]

Love of music

Einstein developed an appreciation of music at an early age. His mother played the piano reasonably well and wanted her son to learn the violin, not only to instill in him a love of music but also to help him assimilate German culture. According to conductor Leon Botstein, Einstein is said to have begun playing when he was five, but did not enjoy it at that age.[107]

When he turned thirteen, however, he discovered the violin sonatas of Mozart. "Einstein fell in love" with Mozart's music, notes Botstein, and learned to play music more willingly. According to Einstein, he taught himself to play without "ever practicing systematically", adding that "Love is a better teacher than a sense of duty."[107] At age seventeen, he was heard by a school examiner in Aarau as he played Beethoven's violin sonatas, the examiner stating afterward that his playing was "remarkable and revealing of 'great insight.'" What struck the examiner, writes Botstein, was that Einstein "displayed a deep love of the music, a quality that was and remains in short supply. Music possessed an unusual meaning for this student."[107]

Botstein notes that music assumed a pivotal and permanent role in Einstein's life from that period on. Although the idea of becoming a professional himself was not on his mind at any time, among those with whom Einstein played chamber music were a few professionals, and he performed for private audiences and friends. Chamber music also became a regular part of his social life while living in Bern, Zurich, and Berlin, where he played with Max Planck and his son, among others. In 1931, while engaged in research at California Institute of Technology, he visited the Zoellner family conservatory in Los Angeles and played some of Beethoven and Mozart's works with members of the Zoellner Quartet, recently retired from two decades of acclaimed touring all across the United States; Einstein later presented the family patriarch with an autographed photograph as a memento.[108][109] Near the end of his life, when the young Juilliard Quartet visited him in Princeton, he played his violin with them; although they slowed the tempo to accommodate his lesser technical abilities, Botstein notes the quartet was "impressed by Einstein's level of coordination and intonation."[107]

Non-scientific legacy

While travelling, Einstein wrote daily to his wife Elsa and adopted stepdaughters Margot and Ilse. The letters were included in the papers bequeathed to The Hebrew University. Margot Einstein permitted the personal letters to be made available to the public, but requested that it not be done until twenty years after her death (she died in 1986[110]). Barbara Wolff, of The Hebrew University's Albert Einstein Archives, told the BBC that there are about 3,500 pages of private correspondence written between 1912 and 1955.[111]

Einstein bequeathed the royalties from use of his image to The Hebrew University of Jerusalem. Corbis, successor to The Roger Richman Agency, licenses the use of his name and associated imagery, as agent for the university.[112]

In popular culture

In the period before World War II, Einstein was so well known in America that he would be stopped on the street by people wanting him to explain "that theory". He finally figured out a way to handle the incessant inquiries. He told his inquirers "Pardon me, sorry! Always I am mistaken for Professor Einstein."[113]

Einstein has been the subject of or inspiration for many novels, films, plays, and works of music.[114] He is a favorite model for depictions of mad scientists and absent-minded professors; his expressive face and distinctive hairstyle have been widely copied and exaggerated. *Time* magazine's Frederic Golden wrote that Einstein was "a cartoonist's dream come true".[]

Awards and honors

Einstein received numerous awards and honors, including the Nobel Prize in Physics.

Publications

> *The following publications by Albert Einstein are referenced in this article. A more complete list of his publications may be found at List of scientific publications by Albert Einstein.*

- Einstein, Albert (1901), "Folgerungen aus den Capillaritätserscheinungen (Conclusions Drawn from the Phenomena of Capillarity)", *Annalen der Physik* **4** (3): 513, Bibcode:1901AnP...309..513E [115], doi:10.1002/andp.19013090306 [116]

- Einstein, Albert (1905a), "Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt (On a Heuristic Viewpoint Concerning the Production and Transformation of Light)" [117], *Annalen der Physik* **17** (6): 132–148, Bibcode:1905AnP...322..132E [118], doi:10.1002/andp.19053220607 [119] This annus mirabilis paper on the photoelectric effect was received by *Annalen der Physik* 18 March.
- Einstein, Albert (1905b), *A new determination of molecular dimensions*. This PhD thesis was completed 30 April and submitted 20 July.
- Einstein, Albert (1905c), "On the Motion – Required by the Molecular Kinetic Theory of Heat – of Small Particles Suspended in a Stationary Liquid", *Annalen der Physik* **17** (8): 549–560, Bibcode:1905AnP...322..549E [120], doi:10.1002/andp.19053220806 [121]. This annus mirabilis paper on Brownian motion was received 11 May.
- Einstein, Albert (1905d), "On the Electrodynamics of Moving Bodies", *Annalen der Physik* **17** (10): 891–921, Bibcode:1905AnP...322..891E [122], doi:10.1002/andp.19053221004 [123]. This annus mirabilis paper on special relativity was received 30 June.
- Einstein, Albert (1905e), "Does the Inertia of a Body Depend Upon Its Energy Content?", *Annalen der Physik* **18** (13): 639–641, Bibcode:1905AnP...323..639E [124], doi:10.1002/andp.19053231314 [125]. This annus mirabilis paper on mass-energy equivalence was received 27 September.
- Einstein, Albert (1915), "Die Feldgleichungen der Gravitation (The Field Equations of Gravitation)", *Königlich Preussische Akademie der Wissenschaften*: 844–847
- Einstein, Albert (1917a), "Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie (Cosmological Considerations in the General Theory of Relativity)", *Königlich Preussische Akademie der Wissenschaften*
- Einstein, Albert (1917b), "Zur Quantentheorie der Strahlung (On the Quantum Mechanics of Radiation)", *Physikalische Zeitschrift* **18**: 121–128, Bibcode:1917PhyZ...18..121E [126]
- Einstein, Albert (11 July 1923), "Fundamental Ideas and Problems of the Theory of Relativity" [127], *Nobel Lectures, Physics 1901–1921*, Amsterdam: Elsevier Publishing Company, archived [128] from the original on 10 February 2007, retrieved 25 March 2007
- Einstein, Albert (1924), "Quantentheorie des einatomigen idealen Gases (Quantum theory of monatomic ideal gases)", *Sitzungsberichte der Preussichen Akademie der Wissenschaften Physikalisch-Mathematische Klasse*: 261–267. First of a series of papers on this topic.
- Einstein, Albert (1926), "Die Ursache der Mäanderbildung der Flussläufe und des sogenannten Baerschen Gesetzes", *Die Naturwissenschaften* **14** (11): 223–224, Bibcode:1926NW.....14..223E [129], doi:10.1007/BF01510300 [130]. On Baer's law and meanders in the courses of rivers.
- Einstein, Albert; Podolsky, Boris; Rosen, Nathan (15 May 1935), "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?", *Physical Review* **47** (10): 777–780, Bibcode:1935PhRv...47..777E [131], doi:10.1103/PhysRev.47.777 [132]
- Einstein, Albert (1940), "On Science and Religion", *Nature* (Edinburgh: Scottish Academic) **146** (3706): 605, Bibcode:1940Natur.146..605E [133], doi:10.1038/146605a0 [134], ISBN 0-7073-0453-9
- Einstein, Albert *et al.* (4 December 1948), "To the editors" [135], *New York Times* (Melville, NY: AIP, American Inst. of Physics), ISBN 0-7354-0359-7
- Einstein, Albert (May 1949), "Why Socialism?" [136], *Monthly Review*, archived [137] from the original on 11 January 2006, retrieved 16 January 2006
- Einstein, Albert (1950), "On the Generalized Theory of Gravitation", *Scientific American*, CLXXXII (4): 13–17
- Einstein, Albert (1954), *Ideas and Opinions*, New York: Random House, ISBN 0-517-00393-7
- Einstein, Albert (1969), *Albert Einstein, Hedwig und Max Born: Briefwechsel 1916–1955* (in German), Munich: Nymphenburger Verlagshandlung, ISBN 3-88682-005-X
- Einstein, Albert (1979), *Autobiographical Notes*, Paul Arthur Schilpp (Centennial ed.), Chicago: Open Court, ISBN 0-87548-352-6. The *chasing a light beam* thought experiment is described on pages 48–51.
- Collected Papers: Stachel, John, Martin J. Klein, a. J. Kox, Michel Janssen, R. Schulmann, Diana Komos Buchwald and others (Eds.) (1987–2006), *The Collected Papers of Albert Einstein, Vol. 1–10* [138], Princeton

University Press Further information about the volumes published so far can be found on the webpages of the Einstein Papers Project [139] and on the Princeton University Press Einstein Page [140]

Notes

[2] Zahar, Élie (2001), *Poincaré's Philosophy. From Conventionalism to Phenomenology*, Carus Publishing Company, Chapter 2, p.41 (http://books.google.com/?id=jJl2JAqvoSAC&pg=PA41), ISBN 0-8126-9435-X.

[4] David Bodanis, *$E = mc^2$: A Biography of the World's Most Famous Equation* (New York: Walker, 2000).

[6] "Scientific Background on the Nobel Prize in Physics 2011. The accelerating universe." (page 2) (http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/advanced-physicsprize2011.pdf) Nobelprize.org.

[7] His non-scientific works include: *About Zionism: Speeches and Lectures by Professor Albert Einstein* (1930), "Why War?" (1933, co-authored by Sigmund Freud), *The World As I See It* (1934), *Out of My Later Years* (1950), and a book on science for the general reader, *The Evolution of Physics* (1938, co-authored by Leopold Infeld).

[8] WordNet for Einstein (http://wordnetweb.princeton.edu/perl/webwn?s=Einstein).

[12] M. Talmey, *The Relativity Theory Simplified and the Formative Period of its Inventor*. Falcon Press, 1932, pp. 161–164.

[13] Dudley Herschbach, "Einstein as a Student", Department of Chemistry and Chemical Biology, Harvard University, Cambridge, MA, USA, pp. 4–5, web: HarvardChem-Einstein-PDF (https://www.chem.purdue.edu/courses/chm374/Articles etc/Herschbach_Einstein_2005.pdf)

[14] "Albert's intellectual growth was strongly fostered at home. His mother, a talented pianist, ensured the children's musical education. His father regularly read Schiller and Heine aloud to the family. Uncle Jakob challenged Albert with mathematical problems, which he solved with 'a deep feeling of happiness'." More significant were the weekly visits of Max Talmud from 1889 through 1894 during which time he introduced the boy to popular scientific texts that brought to an end a short-lived religious phase, convincing him that 'a lot in the Bible stories could not be true'. A textbook of plane geometry that he quickly worked through led on to an avid self-study of mathematics, several years ahead of the school curriculum.<ref> Einstein as a Student (https://www.chem.purdue.edu/courses/chm374/Articles etc/Herschbach_Einstein_2005.pdf), pp. 3–5.

[15] A. Fölsing, *Albert Einstein*, 1997, pp. 30–31.

[16] *Albert Einstein Collected Papers*, vol. 1 (1987), doc. 5.

[18] A. Fölsing, *Albert Einstein*, 1997, pp. 36–37.

[20] A. Fölsing, *Albert Einstein*, 1997, p. 40.

[21] Fölsing 1997, p. 82.

[22] *Collected Papers*, vol. 1, docs. 21-27.

[23] *Albert Einstein Collected Papers*, vol. 1, 1987, doc. 67.

[24] Troemel-Ploetz, D., "Mileva Einstein-Marić: The Woman Who Did Einstein's Mathematics", *Women's Studies Int. Forum*, vol. 13, no. 5, pp. 415–432, 1990.

[26] Pais, A., *Einstein Lived Here*, Oxford University Press, 1994, pp. 1–29.

[27] Holton, G., *Einstein, History, and Other Passions*, Harvard University Press, 1996, pp. 177–193.

[28] Stachel, J., *Einstein from B to Z*, Birkhäuser, 2002, pp. 26–38; 39–55. philoscience.unibe.ch (http://books.google.com/books?id=OAsQ_hFjhrAC&printsec=frontcover&dq=Einstein+from+B+to+Z#v=onepage&q=Einstein from B to Z&f=false)

[29] Martinez, A. A., "Handling evidence in history: the case of Einstein's Wife." *School Science Review*, 86 (316), March 2005, pp. 49–56. PDF (https://webspace.utexas.edu/aam829/1/m/Maric_files/EvidenceMaric.pdf)

[30] J. Renn & R. Schulmann, *Albert Einstein/Mileva Marić: The Love Letters*, 1992, pp. 73–74, 78.

[31] A. Calaprice & T. Lipscombe, *Albert Einstein: A Biography*, 2005, pp. 22–23.

[32] Biography of Grossmann by Mactutor (http://www-history.mcs.st-and.ac.uk/Biographies/Grossmann.html)

[33] Now the . See also their

[34] Peter Galison, "Einstein's Clocks: The Question of Time" *Critical Inquiry* 26, no. 2 (Winter 2000): 355–389.

[35] Peter Galison, "Einstein's Clocks: The Question of Time" *Critical Inquiry* 26, no. 2 (Winter 2000).

[41] Kant, Horst. "Albert Einstein and the Kaiser Wilhelm Institute for Physics in Berlin". in Renn, Jürgen. "Albert Einstein – Chief Engineer of the Universe: One Hundred Authors for Einstein." Ed. Renn, Jürgen. *Wiley-VCH*. 2005. pp. 166–169. ISBN 3-527-40574-7

[42] , Timeline, p. xix (http://books.google.com/books?id=5eWh2O_3OAQC&pg=PR19)

[43] Heilbron, 2000, p. 84.

[48] Hoffman and Dukas (1972), pp. 145–148; Fölsing (1997), pp. 499–508.

[49] Isaacson, Walter. *Einstein: His Life and Universe*, Simon & Schuster (2007)

[50] Isaacson, Walter. *Einstein: His Life and Universe*, Simon & Schuster (2007) pp. 407–410

[51] Fölsing (1997), p. 659.

[52] Isaacson (2007), p. 404.

[53] Hoffman, B. (1972), pp. 165–171

[54] Fölsing, A. (1997), pp. 666–677.

[55] Clark (1971), p. 619.

[56] Fölsing (1997), pp. 649, 678.

[57] Clark (1971), p.642.

[58] Fölsing (1997), pp. 686–687.

[60] Gosling, F.G. *The Manhattan Project: Making the Atomic Bomb*, U.S. Department of Energy, History Division (January 1999) p. vii

[61] Diehl, Sarah J.; Moltz, James Clay. *Nuclear Weapons and Nonproliferation: a Reference Handbook* (http://books.google.com/books?id=3PN-NEfl_U0C&pg=PA218&dq=Einstein+Roosevelt&num=30&cd=4#v=onepage&q=Letter from Einstein Roosevelt&f=false), ABC-CLIO (2008) p. 218

[62] Stern, Fritz. Essay, "Einstein's Germany" (http://books.google.com/books?id=zGzcV40b3IkC&pg=PA97&dq=E=+Einstein's+German+by+Fritz+Stern#v=onepage&q&f=false), *E = Einstein: His Life, His Thought, and His Influence on Our Culture*, Sterling Publishing (2006) pp. 97–118

[63] Einstein: The Life and Times *by Ronald Clark. page 752*

[64] Fred Jerome, Rodger Taylor (2006) *Einstein on Race and Racism* (http://books.google.com/books?id=4d79VQdOfFUC&pg=PR10&dq=Einstein+on+Race+and+Racism+america's+worst+disease#v=onepage&q&f=false) Rutgers University Press, 2006.

[65] Calaprice, Alice (2005) *The new quotable Einstein* (http://press.princeton.edu/titles/7921.html). pp.148–149 Princeton University Press, 2005. See also *Odyssey in Climate Modeling, Global Warming, and Advising Five Presidents* (http://books.google.com/books?id=dLhVn-McDDgC&pg=PA226&dq=racism+americas+worst+disease+1946#v=onepage&q&f=false)

[75] " Einstein archive at the Instituut-Lorentz (http://www.lorentz.leidenuniv.nl/history/Einstein_archive/)". *Instituut-Lorentz.* 2005. Retrieved on 21 November 2005.

[81] For a discussion of the reception of relativity theory around the world, and the different controversies it encountered, see the articles in Thomas F. Glick, ed., *The Comparative Reception of Relativity* (Kluwer Academic Publishers, 1987), ISBN 90-277-2498-9.

[84] .

[85] Celebrating Einstein "Solid Cold". U.S. DOE. (http://www.osti.gov/accomplishments/nuggets/einstein/solidcolda.html), Office of Scientific and Technical Information, 2011.

[87] Levenson, Thomas. " Einstein's Big Idea (http://www.pbs.org/wgbh/nova/einstein/genius/)". *Public Broadcasting Service.* 2005. Retrieved on 25 February 2006.

[88] Albert Einstein, Nobel lecture (http://nobelprize.org/nobel_prizes/physics/laureates/1921/einstein-lecture.html) in 1921

[89] van Dongen, Jeroen (2010) *Einstein's Unification* Cambridge University Press, p.23.

[91] Video: The Elegant Universe: Part 1 | Watch NOVA Online | PBS Video (http://video.pbs.org/video/1512280538). Video.pbs.org. Retrieved on 11 May 2012.

[97] Goettling, Gary. Einstein's refrigerator (http://gtalumni.org/Publications/magazine/sum98/einsrefr.html) *Georgia Tech Alumni Magazine.* 1998. Retrieved on 21 November 2005. Leó Szilárd, a Hungarian physicist who later worked on the Manhattan Project, is credited with the discovery of the chain reaction

[98] http://www.google.com/patents/US1781541

[99] In September 2008 it was reported that Malcolm McCulloch of Oxford University was heading a three-year project to develop more robust appliances that could be used in locales lacking electricity, and that his team had completed a prototype Einstein refrigerator. He was quoted as saying that improving the design and changing the types of gases used might allow the design's efficiency to be quadrupled.

[100] From Albert Einstein: Philosopher-Scientist (1949), publ. Cambridge University Press, 1949. Niels Bohr's report of conversations with Einstein.

[101] . A reprint of this book was published by Edition Erbrich in 1982, ISBN 3-88682-005-X

[106] Isaacson, Walter (2008). *Einstein: His Life and Universe*. New York: Simon and Schuster, pp. 390. (http://books.google.com/books?id=cdxWNE7NY6QC&pg=PT390)

[107] Botstein, Leon; Galison, Peter; Holton, Gerald James; Schweber, Silvan S. *Einstein for the 21st century: His Legacy in Science, Art, and Modern Culture*, Princeton Univ. Press (2008) pp. 161–164

[108] Cariaga, Daniel, "Not Taking It with You: A Tale of Two Estates," *Los Angeles Times* (http://articles.latimes.com/1985-12-22/entertainment/ca-20526_1_life-estate), 22 December 1985. Retrieved April 2012.

[109] Auction listing (http://www.rrauction.com/albert_einstein_signed_photo_to_joseph_zoellner.cfm) by RR Auction, auction closed 13 October 2010.

[113] The New Yorker April 1939 pg 69 Disguise (http://www.newyorker.com/search/query?queryType=nonparsed&query=Einstein+&bylquery=Maloney&month1=01&day1=14&year1=1939&month2=01&day2=14&year2=1939&page=&sort=&submit.x=10&submit.y=5)

[115] http://adsabs.harvard.edu/abs/1901AnP...309..513E

[116] http://dx.doi.org/10.1002%2Fandp.19013090306

[117] http://www.physik.uni-augsburg.de/annalen/history/einstein-papers/1905_17_132-148.pdf

[118] http://adsabs.harvard.edu/abs/1905AnP...322..132E

[119] http://dx.doi.org/10.1002%2Fandp.19053220607

[120] http://adsabs.harvard.edu/abs/1905AnP...322..549E

[121] http://dx.doi.org/10.1002%2Fandp.19053220806

[122] http://adsabs.harvard.edu/abs/1905AnP...322..891E

[123] http://dx.doi.org/10.1002%2Fandp.19053221004

[124] http://adsabs.harvard.edu/abs/1905AnP...323..639E

[125] http://dx.doi.org/10.1002%2Fandp.19053231314

[126] http://adsabs.harvard.edu/abs/1917PhyZ...18..121E
[127] http://nobelprize.org/nobel_prizes/physics/laureates/1921/einstein-lecture.pdf
[128] http://web.archive.org/web/20070210054832/http://nobelprize.org/nobel_prizes/physics/laureates/1921/einstein-lecture.pdf
[129] http://adsabs.harvard.edu/abs/1926NW.....14..223E
[130] http://dx.doi.org/10.1007%2FBF01510300
[131] http://adsabs.harvard.edu/abs/1935PhRv...47..777E
[132] http://dx.doi.org/10.1103%2FPhysRev.47.777
[133] http://adsabs.harvard.edu/abs/1940Natur.146..605E
[134] http://dx.doi.org/10.1038%2F146605a0
[135] http://phys4.harvard.edu/~wilson/NYTimes1948.html
[136] http://www.monthlyreview.org/598einst.htm
[137] http://web.archive.org/web/20060111081948/http://www.monthlyreview.org/598einst.htm
[138] http://press.princeton.edu/einstein/writings.html#papers
[139] http://www.einstein.caltech.edu/index.html
[140] http://press.princeton.edu/einstein/

References

Further reading

- Brian, Denis (1996). *Einstein: A Life.* New York: John Wiley.
- Clark, Ronald (1971). *Einstein: The Life and Times.* New York: Avon Books.
- Fölsing, Albrecht (1997): *Albert Einstein: A Biography*. New York: Penguin Viking. (Translated and abridged from the German by Ewald Osers.) ISBN 978-0-670-85545-2
- Highfield, Roger; Carter, Paul (1993). *The Private Lives of Albert Einstein*. London: Faber and Faber. ISBN 978-0-571-16744-9.
- Hoffmann, Banesh, with the collaboration of Helen Dukas (1972): *Albert Einstein: Creator and Rebel*. London: Hart-Davis, MacGibbon Ltd. ISBN 978-0-670-11181-7
- Isaacson, Walter (2007): *Einstein: His Life and Universe*. Simon & Schuster Paperbacks, New York. ISBN 978-0-7432-6473-0
- Moring, Gary (2004): *The complete idiot's guide to understanding Einstein* (http://books.google.com/books?id=875TTxildJ0C&dq=idiots+guide+to+einstein&printsec=frontcover) (1st ed. 2000). Indianapolis IN: Alpha books (Macmillan USA). ISBN 0-02-863180-3
- Pais, Abraham (1982): *Subtle is the Lord: The science and the life of Albert Einstein*. Oxford University Press. ISBN 978-0-19-853907-0. The definitive biography to date.
- Pais, Abraham (1994): *Einstein Lived Here*. Oxford University Press. ISBN 0-19-280672-6
- Parker, Barry (2000): *Einstein's Brainchild: Relativity Made Relatively Easy!*. Prometheus Books. Illustrated by Lori Scoffield-Beer. A review of Einstein's career and accomplishments, written for the lay public. ISBN 978-1-59102-522-1
- Schweber, Sylvan S. (2008): *Einstein and Oppenheimer: The Meaning of Genius*. Harvard University Press. ISBN 978-0-674-02828-9.
- Oppenheimer, J.R. (1971): "On Albert Einstein," p. 8–12 in *Science and synthesis: an international colloquium organized by Unesco on the tenth anniversary of the death of Albert Einstein and Teilhard de Chardin*, Springer-Verlag, 1971, 208 pp. (Lecture delivered at the UNESCO House in Paris on 13 December 1965.) Also published in The New York Review of Books, 17 March 1966, On Albert Einstein by Robert Oppenheimer (http://www.nybooks.com/articles/archives/1966/mar/17/on-albert-einstein/?pagination=false)

External links

- *Ideas and Opinions*, Einstein's letters and speeches (http://www.scribd.com/doc/23220527/Ideas-and-Opinions-by-Albert-Einstein), Full text, *Crown Publishers (1954) 384 pages*
- Einstein's Scholar Google profile (http://scholar.google.com.au/citations?user=qc6CJjYAAAAJ&hl=en)
- Works by Albert Einstein (public domain in Canada)
- *The MacTutor History of Mathematics archive* (http://www-history.mcs.st-andrews.ac.uk/Biographies/Einstein.html), School of Mathematics and Statistics, University of St Andrews, Scotland, April 1997, retrieved 14 June 2009
- *Why Socialism?* (http://www.monthlyreview.org/598einstein.php) by Albert Einstein, *Monthly Review*, May 1949
- Einstein's Personal Correspondence: Religion, Politics, The Holocaust, and Philosophy (http://www.shapell.org/exhibitions.aspx?einstein-original-letters-in-aid-of-his-brethren) Shapell Manuscript Foundation
- FBI file on Albert Einstein (http://vault.fbi.gov/Albert Einstein)
- Nobelprize.org Biography:Albert Einstein (http://nobelprize.org/nobel_prizes/physics/laureates/1921/einstein-bio.html)
- The Einstein You Never Knew (http://life.tumblr.com/post/526230217/the-einstein-you-never-knew) — slideshow by *Life magazine*
- Albert Einstein (http://www.history.com/topics/albert-einstein) — videos
- Science Odyssey People And Discoveries (http://www.pbs.org/wgbh/aso/databank/entries/bpeins.html)
- MIT OpenCourseWare STS.042J/8.225J: Einstein, Oppenheimer, Feynman: Physics in the 20th century (http://web.archive.org/web/20110608004818/http://ocw.mit.edu/courses/science-technology-and-society/sts-042j-einstein-oppenheimer-feynman-physics-in-the-20th-century-spring-2006/) — free study course that explores the changing roles of physics and physicists during the 20th century
- Albert Einstein Archives Online (80,000+ Documents) (http://www.alberteinstein.info/) (MSNBC - 19 March 2012 (http://www.msnbc.msn.com/id/46785542/ns/technology_and_science-science/))
- Einstein's declaration of intention for American citizenship (http://www.wdl.org/en/item/2745/) from the World Digital Library
- Albert Einstein Collection at Brandeis University (http://archon.brandeis.edu/?p=collections/findingaid&id=41)

Annus Mirabilis and special relativity

Annus Mirabilis papers

The ***Annus Mirabilis*** **papers** (from Latin *annus mīrābilis*, "extraordinary year") are the papers of Albert Einstein published in the *Annalen der Physik* scientific journal in 1905. These four articles contributed substantially to the foundation of modern physics and changed views on space, time, and matter. The *Annus Mirabilis* is often called the "Miracle Year" in English or *Wunderjahr* in German.

Einstein in 1905, when he wrote the *Annus Mirabilis* papers

Background


The *Einsteinhaus* on the Kramgasse in Bern, Einstein's residence at the time. Most of the papers were written in his apartment on the first floor.

At the time the papers were written, Einstein did not have easy access to a complete set of scientific reference materials, although he did regularly read and contribute reviews to *Annalen der Physik*. Additionally, scientific colleagues available to discuss his theories were few. He worked as an examiner at the Patent Office in Bern, Switzerland, and he later said of a co-worker there, Michele Besso, that he "could not have found a better sounding board for his ideas in all of Europe". In addition to co-workers and the other members of the self-styled "Olympian Academy" (Maurice Solovine and Paul Habicht), his wife, Mileva Marić, may have had some influence on Einstein's work but how much is unclear.[1][2][3][4] Through these papers, Einstein tackles some of the era's most important physics questions and problems. In 1900, a lecture titled "Nineteenth-Century Clouds over the Dynamical Theory of Heat and Light",[5] by Lord Kelvin, suggested that physics had no satisfactory explanations for the results of the Michelson-Morley experiment and for black body radiation. As introduced, special relativity provided an account for the results of the Michelson-Morley experiments. Einstein's theories for the photoelectric effect extended the quantum theory which Max Planck had developed in his successful explanation of black body radiation.

Despite the greater fame achieved by his other works, such as that on special relativity, it was his work on the photoelectric effect which won him his Nobel Prize in 1921: "For services to theoretical physics and especially for the discovery of the law of the photoelectric effect." The Nobel committee had waited patiently for experimental confirmation of special relativity; however none was forthcoming until the time dilation experiments of Ives and Stilwell (1938),[6] (1941)[7] and Rossi and Hall (1941).[8]Wikipedia:Disputed statement

Papers

Photoelectric effect

The paper, "On a Heuristic Viewpoint Concerning the Production and Transformation of Light",[9] received March 18 and published June 9, proposed the idea of *energy quanta*. This idea, motivated by Max Planck's earlier derivation of the law of black body radiation, assumes that luminous energy can be absorbed or emitted only in discrete amounts, called *quanta*. Einstein states,

> Energy, during the propagation of a ray of light, is not continuously distributed over steadily increasing spaces, but it consists of a finite number of energy quanta localised at points in space, moving without dividing and capable of being absorbed or generated only as entities.

In explaining the photoelectric effect, the hypothesis that energy consists of *discrete packets*, as Einstein illustrates, can be directly applied to black bodies, as well.

The idea of light quanta contradicts the wave theory of light that follows naturally from James Clerk Maxwell's equations for electromagnetic behavior and, more generally, the assumption of infinite divisibility of energy in physical systems.

> A profound formal difference exists between the theoretical concepts that physicists have formed about gases and other ponderable bodies, and Maxwell's theory of electromagnetic processes in so-called empty space. While we consider the state of a body to be completely determined by the positions and velocities of an indeed

> very large yet finite number of atoms and electrons, we make use of continuous spatial functions to determine the electromagnetic state of a volume of space, so that a finite number of quantities cannot be considered as sufficient for the complete determination of the electromagnetic state of space.
>
> [... this] leads to contradictions when applied to the phenomena of emission and transformation of light.
>
> According to the view that the incident light consists of energy quanta *[...],* the production of cathode rays by light can be conceived in the following way. The body's surface layer is penetrated by energy quanta whose energy is converted at least partially into kinetic energy of the electrons. The simplest conception is that a light quantum transfers its entire energy to a single electron [...]

Einstein noted that the photoelectric effect depended on the wavelength, and hence the frequency of the light. At too low a frequency, even intense light produced no electrons. However, once a certain frequency was reached, even low intensity light produced electrons. He compared this to Planck's hypothesis that light could be emitted only in packets of energy given by hf, where h is Planck's constant and f is the frequency. He then postulated that light travels in packets whose energy depends on the frequency, and therefore only light above a certain frequency would bring sufficient energy to liberate an electron.

Even after experiments confirmed that Einstein's equations for the photoelectric effect were accurate, his explanation was not universally accepted. Niels Bohr, in his 1922 Nobel address, stated, "The hypothesis of light-quanta is not able to throw light on the nature of radiation."

By 1921, when Einstein was awarded the Nobel Prize and his work on photoelectricity was mentioned by name in the award citation, some physicists accepted that the equation ($hf=\Phi+E_k$) was correct and light quanta were possible. In 1923, Arthur Compton's X-ray scattering experiment helped more of the scientific community to accept this formula. The theory of light quanta was a strong indicator of wave-particle duality, a fundamental principle of quantum mechanics.[10] A complete picture of the theory of photoelectricity was realized after the maturity of quantum mechanics.

Brownian motion

The article "Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen" ("On the Motion of Small Particles Suspended in a Stationary Liquid, as Required by the Molecular Kinetic Theory of Heat"),[11] received May 11 and published July 18, delineated a stochastic model of Brownian motion.

> In this paper it will be shown that, according to the molecular kinetic theory of heat, bodies of a microscopically visible size suspended in liquids must, as a result of thermal molecular motions, perform motions of such magnitudes that they can be easily observed with a microscope. It is possible that the motions to be discussed here are identical with so-called Brownian molecular motion; however, the data available to me on the latter are so imprecise that I could not form a judgment on the question ...

Einstein derived expressions for the mean squared displacement of particles. Using the kinetic theory of fluids, which at the time was controversial, the article established the phenomenon, which was lacking a satisfactory explanation even decades after the first observation, provided empirical evidence for the reality of the atom. It also lent credence to statistical mechanics, which had been controversial at that time, as well. Before this paper, atoms were recognized as a useful concept, but physicists and chemists debated whether atoms were real entities. Einstein's statistical discussion of atomic behavior gave experimentalists a way to count atoms by looking through an ordinary microscope. Wilhelm Ostwald, one of the leaders of the anti-atom school, later told Arnold Sommerfeld that he had been convinced of the existence of atoms by Einstein's complete explanation of Brownian motion.[*citation needed*]

Special relativity

Einstein's "Zur Elektrodynamik bewegter Körper" ("On the Electrodynamics of Moving Bodies"),[12] his third paper that year, was received on June 30 and published September 26. 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.

The paper mentions the names of only five other scientists, Isaac Newton, James Clerk Maxwell, Heinrich Hertz, Christian Doppler, and Hendrik Lorentz. It does not have any references to any other publications. Many of the ideas had already been published by others, as detailed in history of special relativity and relativity priority dispute. However, Einstein's paper introduces a theory of time, distance, mass, and energy that was consistent with electromagnetism, but omitted the force of gravity.

At the time, it was known that Maxwell's equations, when applied to moving bodies, led to asymmetries (Moving magnet and conductor problem), and that it had not been possible to discover any motion of the Earth relative to the 'light medium'. Einstein puts forward two postulates to explain these observations. First, he applies the principle of relativity, which states that the laws of physics remain the same for any non-accelerating frame of reference (called an inertial reference frame), to the laws of electrodynamics and optics as well as mechanics. In the second postulate, Einstein proposes that the speed of light has the same value in all inertial frames of reference, independent of the state of motion of the emitting body.

Special relativity is thus consistent with the result of the Michelson–Morley experiment, which had not detected a medium of conductance (or aether) for light waves unlike other known waves that require a medium (such as water or air). Einstein may not have known about that experiment, but states,

> Examples of this sort, together with the unsuccessful attempts to discover any motion of the earth relatively to the "light medium," suggest that the phenomena of electrodynamics as well as of mechanics possess no properties corresponding to the idea of absolute rest.

The speed of light is fixed, and thus *not* relative to the movement of the observer. This was impossible under Newtonian classical mechanics. Einstein argues,

> … the same laws of electrodynamics and optics will be valid for all frames of reference for which the equations of mechanics hold good. We will raise this conjecture (the purport of which will hereafter be called the "Principle of Relativity") to the status of a postulate, and also introduce another postulate, which is only apparently irreconcilable with the former, namely, that light is always propagated in empty space with a definite velocity **c** which is independent of the state of motion of the emitting body. These two postulates suffice for the attainment of a simple and consistent theory of the electrodynamics of moving bodies based on Maxwell's theory for stationary bodies. The introduction of a "luminiferous ether" will prove to be superfluous in as much as the view here to be developed will not require an "absolutely stationary space" provided with special properties, nor assign a velocity-vector to a point of the empty space in which electromagnetic processes take place.
>
> The theory *[…]* is based—like all electrodynamics—on the kinematics of the rigid body, since the assertions of any such theory have to do with the relationships between rigid bodies (systems of co-ordinates), clocks, and electromagnetic processes. Insufficient consideration of this circumstance lies at the root of the difficulties which the electrodynamics of moving bodies at present encounters.

It had previously been proposed, by George FitzGerald in 1889 and by Lorentz in 1892, independently of each other, that the Michelson-Morley result could be accounted for if moving bodies were contracted in the direction of their motion. Some of the paper's core equations, the Lorentz transforms, had been published by Joseph Larmor (1897, 1900), Hendrik Lorentz (1895, 1899, 1904) and Henri Poincaré (1905), in a development of Lorentz's 1904 paper. Einstein's presentation differed from the explanations given by FitzGerald, Larmor, and Lorentz, but was similar in many respects to the formulation by Poincaré (1905).

His explanation arises from two axioms. First, Galileo's idea that the laws of nature should be the same for all observers that move with constant speed relative to each other. Einstein writes,

> The laws by which the states of physical systems undergo change are not affected, whether these changes of state be referred to the one or the other of two systems of co-ordinates in uniform translatory motion.

The second is the rule that the speed of light is the same for every observer.

> Any ray of light moves in the "stationary" system of co-ordinates with the determined velocity c, whether the ray be emitted by a stationary or by a moving body.

The theory, now called the special theory of relativity, distinguishes it from his later general theory of relativity, which considers all observers to be equivalent. Special relativity gained widespread acceptance remarkably quickly, confirming Einstein's comment that it had been "ripe for discovery" in 1905. Acknowledging the role of Max Planck in the early dissemination of his ideas, Einstein wrote in 1913 "The attention that this theory so quickly received from colleagues is surely to be ascribed in large part to the resoluteness and warmth with which he [Planck] intervened for this theory". In addition, the improved mathematical formulation of the theory by Hermann Minkowski in 1907 was influential in gaining acceptance for the theory. Also, and most importantly, the theory was supported by an ever-increasing body of confirmatory experimental evidence.

Mass–energy equivalence

On November 21 *Annalen der Physik* published a fourth paper (received September 27), "Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig?" ("Does the Inertia of a Body Depend Upon Its Energy Content?"),[13] in which Einstein developed an argument for arguably the most famous equation in the field of physics: $E = mc^2$. Einstein considered the equivalency equation to be of paramount importance because it showed that a massive particle possesses an energy, the "rest energy", distinct from its classical kinetic and potential energies.

The paper is based on James Clerk Maxwell's and Heinrich Rudolf Hertz's investigations and, in addition, the axioms of relativity, as Einstein states,

> The results of the previous investigation lead to a very interesting conclusion, which is here to be deduced.
>
> The previous investigation was based "on the Maxwell-Hertz equations for empty space, together with the Maxwellian expression for the electromagnetic energy of space ..."
>
> The laws by which the states of physical systems alter are independent of the alternative, to which of two systems of coordinates, in uniform motion of parallel translation relatively to each other, these alterations of state are referred (principle of relativity).

The equation sets forth that energy of a body at rest (E) equals its mass (m) times the speed of light (c) squared, or $E = mc^2$.

> If a body gives off the energy L in the form of radiation, its mass diminishes by L/c^2. The fact that the energy withdrawn from the body becomes energy of radiation evidently makes no difference, so that we are led to the more general conclusion that
>
> The mass of a body is a measure of its energy-content; if the energy changes by L, the mass changes in the same sense by $L/9 \times 10^{20}$, the energy being measured in ergs, and the mass in grammes.
>
> [...]
>
> If the theory corresponds to the facts, radiation conveys inertia between the emitting and absorbing bodies.

The mass-energy relation can be used to predict how much energy will be released or consumed by nuclear reactions; one simply measures the mass of all constituents and the mass of all the products and multiplies the difference between the two by c^2. The result shows how much energy will be released or consumed, usually in the form of light or heat. When applied to certain nuclear reactions, the equation shows that an extraordinarily large amount of energy will be released, much larger than in the combustion of chemical explosives, where the mass difference is hardly measurable at all. This explains why nuclear weapons produce such phenomenal amounts of energy, as they release binding energy during nuclear fission and nuclear fusion, and also convert a much larger portion of subatomic mass to energy.

Commemoration

The International Union of Pure and Applied Physics (IUPAP) resolved to commemorate the 100th year of the publication of Einstein's extensive work in 1905 as the 'World Year of Physics 2005'. This was subsequently endorsed by the United Nations.

Notes

[1] The suggestion that Mileva actually co-authored some of Einstein's early papers was based largely on what is now generally agreed to have been a misunderstanding. In an obituary for Einstein in 1955, Abram Joffe wrote "In 1905, three articles appeared in the *Annalen der Physik*... The author of these articles, an unknown person at the time, was a bureaucrat at the Patent Office in Bern, Einstein-Marity (Marity - the maiden name of his wife, which by Swiss custom is added to the husband's family name)." Thus Joffe did not claim co-authorship, he merely stated that the papers were by an unknown individual, and that Marity was the maiden name of the author's wife, appended to the author's name by Swiss custom. Joffe's comment was later mis-quoted in a way that suggested co-authorship of the husband and wife.

[2] "*Einstein's Wife : The Mileva Question* (http://www.pbs.org/opb/einsteinswife/science/mquest.htm)". Oregon Public Broadcasting, 2003.

[3] Stachel, John, *Einstein's Miraculous Year* (1905), pp. liv-lxiii (http://www.esterson.org/Stachel_Joffe.htm)

[4] Calaprice, Alice, "*The Einstein almanac*". Johns Hopkins University Press, Baltimore, Md. 2005.

[5] *The London, Edinburgh and Dublin Philosophical Magazine and Journal of Science*, Series 6, volume 2, page 1 (1901)

English translations:

- " On a Heuristic Point of View about the Creation and Conversion of Light (http://www.physik.fu-berlin.de/~kleinert/files/eins_lq.pdf)". Translated by Dirk ter Haar
- "On a Heuristic Point of View about the Creation and Conversion of Light. Translated by Wikisource

[10] Physical systems can display both wave-like and particle-like properties

English translation:

- " Investigations on the theory of Brownian Movement (http://users.physik.fu-berlin.de/~kleinert/files/eins_brownian.pdf)". Translated by A.D Cowper

[12] See also a digitized version at Wikilivres:Zur Elektrodynamik bewegter Körper.

English translations:

- " On the Electrodynamics of Moving Bodies (http://www.fourmilab.ch/etexts/einstein/specrel/www/)". Translation by George Barker Jeffery and Wilfrid Perrett in *The Principle of Relativity*, London: Methuen and Company, Ltd. (1923)
- "On the Electrodynamics of Moving Bodies". Translation by Megh Nad Saha in *The Principle of Relativity: Original Papers by A. Einstein and H. Minkowski*, University of Calcutta, 1920, pp. 1–34:

English translations:

- " Does the Inertia of a Body Depend Upon Its Energy Content? (http://www.fourmilab.ch/etexts/einstein/E_mc2/www/)". Translation by George Barker Jeffery and Wilfrid Perrett in *The Principle of Relativity*, London: Methuen and Company, Ltd. (1923).

Works by Einstein

Further reading

- Stachel, John, et al., *Einstein's Miraculous Year*. Princeton University Press, 1998. ISBN 0-691-05938-1
- Renn, Jürgen, and Dieter Hoffmann, "1905 — a miraculous year". 2005 *J. Phys. B: At. Mol. Opt. Phys.* 38 S437-S448 (Max Planck Institute for the History of Science) [Issue 9 (14 May 2005)]

External links

- (http://users.physik.fu-berlin.de/~kleinert/files/) - collection of the Annus Mirabilis papers and their English translations.
- On the Electrodynamics of Moving Bodies (1923 edition)

History of special relativity

The **history of special relativity** consists of many theoretical results and empirical findings obtained by Albert Michelson, Hendrik Lorentz, Henri Poincaré and others. It culminated in the theory of special relativity proposed by Albert Einstein, and subsequent work of Max Planck, Hermann Minkowski and others.

Introduction

Although Isaac Newton based his theory on absolute time and space, he also adhered to the principle of relativity of Galileo Galilei. This stated that all observers who move uniformly relative to each other are equal and no absolute state of motion can be attributed to any observer. During the 19th century the aether theory was widely accepted, mostly in the form given by James Clerk Maxwell. According to Maxwell *all* optical and electrical phenomena propagate in a medium. Thus it seemed possible to determine *absolute* motion relative to the aether and therefore to disprove Galileo's principle.

The failure of any experiment to detect motion through the aether led Hendrik Lorentz in 1892 to develop a theory based on an immobile aether and the Lorentz transformation. Based on Lorentz's aether, Henri Poincaré in 1905 proposed the *relativity principle* as a general law of nature, including electrodynamics and gravitation. In the same year, Albert Einstein published what is now called special relativity – he radically reinterpreted Lorentzian electrodynamics by changing the concepts of space and time and abolishing the aether. This paved the way to general relativity. Subsequent work of Hermann Minkowski laid the foundations of relativistic field theories.

Aether and Electrodynamics of Moving Bodies

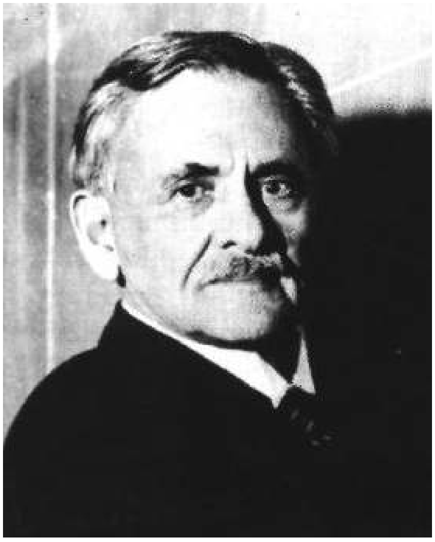
Aether models and Maxwell's equations

Following the work of Thomas Young (1804) and Augustin-Jean Fresnel (1816), it was believed that light propagates as a transverse wave within an elastic medium called luminiferous aether. However, a distinction was made between optical and electrodynamical phenomena so it was necessary to create specific aether models for all phenomena. Attempts to unify those models or to create a complete mechanical description of them did not succeed,[1] but after considerable work by many scientists, including Michael Faraday and Lord Kelvin, James Clerk Maxwell (1864) developed an accurate theory of electromagnetism by deriving a set of equations in electricity, magnetism and inductance, named Maxwell's equations. He first proposed that light was in fact undulations (Electromagnetic radiation) in the *same* aetherial medium that is the cause of electric and magnetic phenomena. However, Maxwell's theory was unsatisfactory regarding the optics of moving bodies, and while he was able to present a complete mathematical model, he was not able to provide a coherent mechanical description of the aether.[2]

After Heinrich Hertz in 1887 demonstrated the existence of electromagnetic waves, Maxwell's theory was widely accepted. In addition, Oliver Heaviside and Hertz further developed the theory and introduced modernized versions of Maxwell's equations. The "Maxwell-Hertz" or "Heaviside-Hertz" Equations subsequently formed an important basis for the further development of electrodynamics, and Heaviside's notation is still used today. Other important contributions to Maxwell's theory were made by George FitzGerald, Joseph John Thomson, John Henry Poynting, Hendrik Lorentz, and Joseph Larmor.[3][4]

Search for the aether

Regarding the relative motion and the mutual influence of matter and aether, two theories were considered: The one of Fresnel (and subsequently Lorentz), who developed a Stationary Aether Theory in which light propagates as a transverse wave and aether was partially dragged with a certain coefficient by matter. Based on this assumption, Fresnel was able to explain the Aberration of light and many optical phenomena.[5] On the other hand, George Gabriel Stokes stated in 1845 that the aether was *fully* dragged by matter (later this view was also shared by Hertz). In this model the aether might be (by analogy with pine pitch) rigid for fast objects and fluid for slower objects. Thus the Earth could move through it fairly freely, but it would be rigid enough to transport light.[6] Fresnel's theory was preferred because his dragging coefficient was confirmed by the Fizeau experiment of Hippolyte Fizeau in 1851, who measured the speed of light in moving liquids.[7]



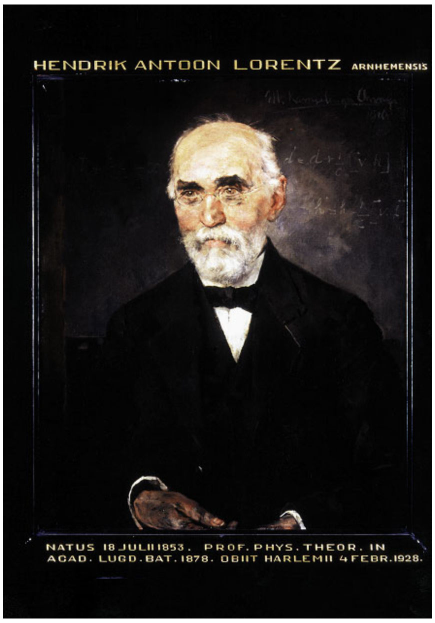
Albert Abraham Michelson

Albert Abraham Michelson (1881) tried to measure the relative motion of earth and Aether (Aether-Wind), as it was expected in Fresnel’s theory, by using an interferometer. He could not determine any relative motion, so he interpreted the result as a confirmation of the thesis of Stokes.[8] However, Lorentz (1886) showed Michelson's calculations were wrong and that he overestimated the accuracy of the measurement. This, together with the large margin of error, made the result of Michelson's experiment inconclusive. In addition, Lorentz showed that Stokes' completely dragged aether lead to contradictory consequences, and therefore he supported an aether theory similar to Fresnel's.[9] To check Fresnel's theory again, Michelson and Edward Morley (1886) performed a repetition of the Fizeau experiment. Fresnel's dragging coefficient was confirmed very exactly on that occasion, and Michelson was now of the opinion that Fresnel's stationary aether theory is correct.[10] To clarify the situation, Michelson and Morley (1887) repeated Michelson's 1881-experiment, and they substantially increased the accuracy of the measurement. However, this now famous Michelson-Morley experiment again yielded a negative result, i.e., no motion of the apparatus through the aether was detected (although the Earth velocity is 60 km/s different in winter than summer). So the physicists were confronted with two seemingly contradictory experiments: The 1886-experiment as an apparent confirmation of Fresnel's stationary aether, and the 1887-experiment as an apparent confirmation of Stokes' completely dragged aether.[11]

A possible solution to the problem was shown by Woldemar Voigt (1887), who investigated the Doppler Effect for waves propagating in an incompressible elastic medium and deduced transformation relations that left the Wave equation in free space unchanged, and explained the negative result of the Michelson-Morley Experiment. The Voigt-Transformations include the Lorentz factor $1/\sqrt{1-v^2/c^2}$ for the y- and z-coordinates, and a new time variable $t'=t-vx/c^2$ which later was called "local time". However, Voigt's work was completely ignored by his contemporaries.[12][13]

FitzGerald (1889) offered another explanation of the negative result of the Michelson-Morley experiment. Contrary to Voigt, he speculated that the intermolecular forces are possibly of electrical origin so that material bodies would contract in the line of motion (length contraction). This was in connection with the work of Heaviside (1887), who determined that the electrostatic fields in motion were deformed (Heaviside Ellipsoid), which leads to physically undetermined conditions at the speed of light.[14] However, Fitzgerald's idea remained widely unknown and was not discussed before Oliver Lodge published a summary of the idea in 1892.[15] Also Lorentz (1892b) proposed length contraction independently from Fitzgerald in order to explain the Michelson-Morley experiment. For plausibility reasons, Lorentz referred to the analogy of the contraction of electrostatic fields. However, even Lorentz admitted that that was not a necessary reason and length-contraction consequently remained an Ad hoc hypothesis.[16][17]

Lorentz's theory of electrons



Hendrik Antoon Lorentz

Lorentz (1892a) set the foundations of Lorentz aether theory, by assuming the existence of electrons which he separated from the aether, and by replacing the "Maxwell-Hertz" Equations by the "Maxwell-Lorentz" Equations. In his model, the aether is completely motionless and, contrary to Fresnel's theory, also is not partially dragged by matter. An important consequence of this notion was that the velocity of light is totally independent of the velocity of the source. Lorentz gave no statements about the mechanical nature of the aether and the electromagnetic processes, but, vice-versa, tried to explain the mechanical processes by electromagnetic ones and therefore created an abstract electromagnetic æther. In the framework of his theory, Lorentz calculated, like Heaviside, the contraction of the electrostatic fields.[18] Lorentz (1895) also introduced what he called the "Theorem of Corresponding States" for terms of first order in v/c. This theorem states that a moving observer (relative to the aether) in his "fictitious" field makes the same observations as a resting observer in his "real" field. An important part of it was local time $t'=t-vx/c^2$, which paved the way to the Lorentz Transformation and which he introduced independently of Voigt. With the help of this concept, Lorentz could explain the aberration of light, the Doppler effect and the Fizeau experiment as well. However, Lorentz's local time was only an auxiliary mathematical tool to simplify the transformation from one system into another – it was Poincaré in 1900 who recognized that "local time" is actually indicated by moving clocks.[19][20][21] Lorentz also recognized that his theory violated the principle of action and reaction, since the aether acts on matter, but matter cannot act on the immobile aether.[22]

A very similar model was created by Joseph Larmor (1897, 1900). Larmor was the first to put Lorentz's 1895-transformation into a form algebraically equivalent to the modern Lorentz transformations, however, he stated that his transformations preserved the form of Maxwell's equations only to second order of v/c. Lorentz later noted that these transformations did in fact preserve the form of Maxwell's equations to all orders of v/c. Larmor noticed on that occasion, that not only can length-contraction be derived from it, but he also calculated some sort of time dilation for electron orbits. Larmor specified his considerations in 1900 and 1904.[13][23] Independently of Larmor, also Lorentz (1899) extended his transformation for second order terms and noted a (mathematical) Time Dilation effect as well.

However, besides Lorentz and Larmor also other physicists tried to develop a consistent model of electrodynamics. For example, Emil Cohn (1900, 1901) created an alternative Electrodynamics in which he, as one of the first, discarded the existence of the aether (at least in the previous form) and would use, like Ernst Mach, the fixed stars as a reference frame instead. Due to inconsistencies within his theory, like different light speeds in different directions, it was superseded by Lorentz's and Einstein's.[24]

Electromagnetic mass

During his development of Maxwell's Theory, J. J. Thomson (1881) recognized that charged bodies are harder to set in motion than uncharged bodies. He also noticed that the mass of a body *in motion* is increased by a constant quantity. Electrostatic fields behave as if they add an "electromagnetic mass" to the mechanical mass of the bodies. I.e., according to Thomson, electromagnetic energy corresponds to a certain mass. This was interpreted as some form of self-inductance of the electromagnetic field.[25][26] Thomson's work was continued and perfected by FitzGerald, Heaviside (1888), and George Frederick Charles Searle (1896, 1897). For the electromagnetic mass they gave — in modern notation — the formula $m=(4/3)E/c^2$, where m is the electromagnetic mass and E is the electromagnetic energy. Heaviside and Searle also recognized that the increase of the mass of a body is not constant and varies with its velocity. Consequently, Searle noted the impossibility of superluminal velocities, because infinite energy would be needed to exceed the speed of light. Also for Lorentz (1899), the integration of the speed-dependence of masses recognized by Thomson was especially important. He noticed that the mass not only varied due to speed, but is also dependent on the direction, and he introduced what Abraham later called "longitudinal" and "transverse" mass. (The transversal mass corresponds to what later was called relativistic mass).[27]

Wilhelm Wien (1900) assumed (following the works of Thomson, Heaviside, and Searle) that the *entire* mass is of electromagnetic origin, which was formulated in the context that all forces of nature are electromagnetic ones (the "Electromagnetic World View"). Wien stated that, if it is assumed that gravitation is an electromagnetic effect too, then there has to be a proportionality between electromagnetic energy, inertial mass and gravitational mass.[28] In the same paper Henri Poincaré (1900b) found another way of combining the concepts of mass and energy. He recognized that electromagnetic energy behaves like a fictitious fluid with mass density of $m=E/c^2$(or $E=mc^2$) and defined a fictitious electromagnetic momentum as well. However, he arrived at a radiation paradox which was fully explained by Einstein in 1905.[29]

Walter Kaufmann (1901–1903) was the first to confirm the velocity dependence of electromagnetic mass by analyzing the ratio e/m (where e is the charge and m the mass) of cathode rays. He found that the value of e/m decreased with the speed, showing that, assuming the charge constant, the mass of the electron increased with the speed. He also believed that those experiments confirmed the assumption of Wien, that there is no "real" mechanical mass, but only the "apparent" electromagnetic mass, or in other words, the mass of all bodies is of electromagnetic origin.[30]

Max Abraham (1902–1904), who was a supporter of the electromagnetic world view, quickly offered an explanation for Kaufmann's experiments by deriving expressions for the electromagnetic mass. Together with this concept, Abraham introduced (like Poincaré in 1900) the notion of "Electromagnetic Momentum" which is proportional to E/c^2. But unlike the fictitious quantities introduced by Poincaré, he considered it as a *real* physical entity. Abraham also noted (like Lorentz in 1899) that this mass also depends on the direction and coined the names "Longitudinal" and "Transverse" Mass. In contrast to Lorentz, he didn't incorporate the Contraction Hypothesis into his theory, and therefore his mass terms differed from those of Lorentz.[31]

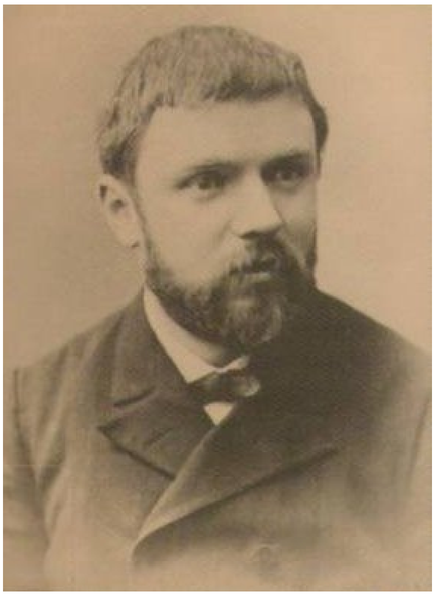
Based on the preceding work on electromagnetic mass, Friedrich Hasenöhrl suggested that part of the mass of a body (which he called apparent mass) can be thought of as radiation bouncing around a cavity. The "apparent mass" of radiation depends on the temperature (because every heated body emits radiation) and is proportional to its energy. Hasenöhrl stated that this energy-apparent-mass relation only holds as long a body radiates, i.e., if the temperature of a body is greater than 0 K. At first he gave the expression $m=(8/3)E/c^2$ for the apparent mass, however, Abraham and Hasenöhrl himself in 1905 changed the result to $m=(4/3)E/c^2$, the same value as for the electromagnetic mass for a body at rest.[32]

Absolute space and time

Some scientists started to criticize Newton's definitions of absolute space and time.[33][34][35] Ernst Mach (1883) argued that absolute time and space are meaningless and only relative motion is a useful concept. He also said that even accelerated motion such as rotation could be related to the fixed stars without using Newton's absolute space. And Carl Neumann (1870) introduced a "Body alpha", which represents some sort of rigid and fixed body for defining inertial motion. Based on the definition of Neumann, Heinrich Streintz (1883) argued that if gyroscopes don't measure any signs of rotation, then one can speak of inertial motion which is related to a "Fundamental body" and a "Fundamental Coordinate System". Eventually, Ludwig Lange (1885) was the first to coin the expression inertial frame of reference and *inertial time scale* as operational replacements for absolute space and time, by defining "*a reference frame in which a mass point thrown from the same point in three different (non co-planar) directions follows rectilinear paths each time it is thrown is called a inertial frame*". And in 1902, Henri Poincaré published the philosophical and popular-science book "Science and Hypothesis", which included: philosophical assessments on the relativity of space, time, and simultaneity; the opinion that a violation of the Relativity Principle can never be detected; the possible non-existence of the aether but also some arguments supporting the aether; many remarks on non-Euclidean geometry.

There were also some attempts to use time as a fourth dimension.[36][37] This was done as early as 1754 by Jean le Rond d'Alembert in the Encyclopédie, and by some authors in the 19th century like H. G. Wells in his novel The Time Machine (1895). In 1901 a philosophical model was developed by Menyhért Palágyi, in which space and time were only two sides of some sort of "spacetime".[38] He used time as an imaginary fourth dimension, which he gave the form it (where $i=\sqrt{-1}$, i.e. imaginary number). However, Palagyi's time coordinate is not connected to the speed of light. He also rejected any connection with the existing constructions of *n*-dimensional spaces and non-Euclidean geometry, so his philosophical model bears only little resemblance with spacetime physics, as it was later developed by Minkowski.[39]

Light constancy and the principle of relative motion



Henri Poincaré

In the second half of the 19th century there were many attempts to develop a worldwide clock network synchronized by electrical signals. On that occasion, the finite propagation speed of light had to be considered as well. So Henri Poincaré (1898) in his paper The Measure of Time drew some important consequences of this process and explained that astronomers, in determining the speed of light, simply assume that light has a constant speed, and that this speed is the same in all directions. Without this postulate it would be impossible to infer the speed of light from astronomical observations, as Ole Rømer did based on observations of the moons of Jupiter. Poincaré also noted that the propagation speed of light can be (and in practice often is) used to define simultaneity between spatially separate events. He concluded by saying, that "*The simultaneity of two events, or the order of their succession, the equality of two durations, are to be so defined that the enunciation of the natural laws may be as simple as possible. In other words, all these rules, all these definitions are only the fruit of an unconscious opportunism.*"[40]

In some other papers, Poincaré (1895, 1900a) argued that experiments like that of Michelson-Morley show the impossibility of detecting the absolute motion of matter, i.e., the relative motion of matter in relation to the aether.

He called this the "principle of relative motion."[41] In the same year he interpreted Lorentz's local time as the result of a synchronization procedure based on light signals. He assumed that 2 observers A and B, which are moving in the aether, synchronize their clocks by optical signals. Since they believe themselves to be at rest, they must consider only the transmission time of the signals and then cross-reference their observations to examine whether their clocks are synchronous. However, from the point of view of an observer at rest in the aether, the clocks are not synchronous and indicate the local time $t'=t-vx/c^2$. But because the moving observers do not know anything about their movement, they do not recognize this. So, contrary to Lorentz, Poincaré-defined local time can be measured and indicated by clocks.[42] Therefore, in his recommendation of Lorentz for the Nobel Prize in 1902, Poincaré argued that Lorentz has convincingly explained the negative outcome of the aether drift experiments by inventing the "diminished time", i.e. that two events at different place could appear as simultaneous, although they are not simultaneous in reality.[43]

Like Poincaré, Alfred Bucherer (1903) believed in the validity of the relativity principle within the domain of electrodynamics, but contrary to Poincaré, Bucherer even assumed that this implies the nonexistence of the aether. However, the theory that was created by him later in 1906 was incorrect and not self-consistent, and the Lorentz transformation was absent within his theory as well.[44]

Lorentz's 1904 model

In his paper Electromagnetic phenomena in a system moving with any velocity smaller than that of light, Lorentz (1904) was following the suggestion of Poincaré and attempted to create a formulation of Electrodynamics, which explains the failure of all known aether drift experiments, i.e. the validity of the relativity principle. He tried to prove the applicability of the Lorentz transformation for all orders, although he didn't succeed completely. Like Wien and Abraham, he argued that there exists only electromagnetic mass, not mechanical mass, and derived the correct expression for longitudinal and transverse mass, which were in agreement with Kaufmann's experiments (even though those experiments were not precise enough to distinguish between the theories of Lorentz and Abraham). And using the electromagnetic momentum, he could explain the negative result of the Trouton-Noble experiment, in which a charged parallel-plate capacitor moving through the aether should orient itself perpendicular to the motion. Also the Experiments of Rayleigh and Brace could be explained. Another important step was the postulate that the Lorentz Transformation has to be valid for non-electrical forces as well.[45]

At the same time, when Lorentz worked out his theory, Wien (1903) recognized an important consequence of the velocity dependence of mass. He argued that superluminal velocities were impossible, because that would require an infinite amount of energy — the same was already noted by Thomson (1893) and Searle (1897). And in June 1904, after he had read Lorentz's 1904 paper, he noticed the same in relation to length contraction, because at superluminal velocities the factor $\sqrt{1-v^2/c^2}$ becomes imaginary.[46]

Lorentz's theory was criticized by Abraham, who demonstrated that on one side the theory obeys the relativity principle, and on the other side the electromagnetic origin of all forces is assumed. Abraham showed, that both assumptions were incompatible, because in Lorentz's theory of the contracted electrons, non-electric forces were needed in order to guarantee the stability of matter. However, in Abraham's theory of the rigid electron, no such forces were needed. Thus the question arose whether the Electromagnetic conception of the world (compatible with Abraham's theory) or the Relativity Principle (compatible with Lorentz's Theory) was correct.[47]

In a September 1904 lecture in St. Louis named The Principles of Mathematical Physics, Poincaré drew some consequences from Lorentz's theory and defined (in modification of Galileo's Relativity Principle and Lorentz's Theorem of Corresponding States) the following principle: "*The Principle of Relativity, according to which the laws of physical phenomena must be the same for a stationary observer as for one carried along in a uniform motion of translation, so that we have no means, and can have none, of determining whether or not we are being carried along in such a motion.*" He also specified his clock synchronization method and explained the possibility of a "new method" or "new mechanics", in which no velocity can surpass that of light for *all* observers. However, he critically noted that the Relativity Principle, Newton's action and reaction, the Conservation of Mass, and the Conservation of

Energy are not fully established and are even threatened by some experiments.[48]

Also Emil Cohn (1904) continued to develop his alternative model (as described above), and while comparing his theory with that of Lorentz, he discovered some important physical interpretations of the Lorentz transformations. He illustrated (like Joseph Larmor in the same year) this transformation by using rods and clocks: If they are at rest in the aether, they indicate the true length and time, and if they are moving, they indicate contracted and dilated values. Like Poincaré, Cohn defined local time as the time, which is based on the assumption of isotropic propagation of light. Contrary to Lorentz and Poincaré it was noticed by Cohn, that within Lorentz's theory the separation of "real" and "apparent" coordinates is artificial, because no experiment can distinguish between them. Yet according to Cohn's own theory, the Lorentz transformed quantities would only be valid for optical phenomena, while mechanical clocks would indicate the "real" time.[24]

Poincaré's Dynamics of the electron

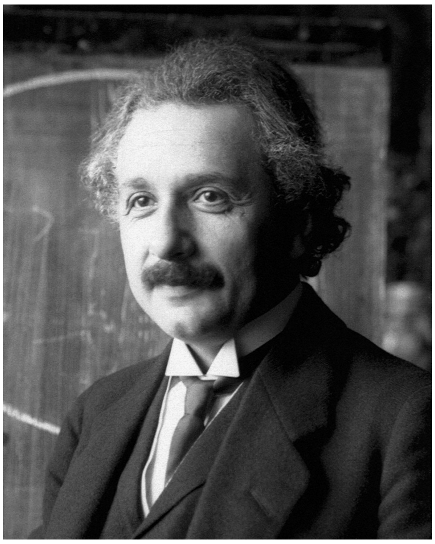
On 5 June 1905, Henri Poincaré submitted the summary of a work which closed the existing gaps of Lorentz's work. (This short paper contained the results of a more complete work which was published in January 1906). He showed that Lorentz's equations of electrodynamics were not fully Lorentz-covariant. So he pointed out the group characteristics of the transformation, and he corrected Lorentz's formulas for the transformations of charge density and current density (which implicitly contained the relativistic velocity-addition formula, which he elaborated in May in a letter to Lorentz). Poincaré used for the first time the term "Lorentz transformation", and he gave them the symmetrical form which is used to this day. He introduced a non-electrical binding force (the so-called "Poincaré stresses") to ensure the stability of the electrons and to explain length contraction. He also sketched a Lorentz-invariant model of gravitation (including gravitational waves) by extending the validity of Lorentz-invariance to non-electrical forces.[49][50]

Eventually Poincaré (independently of Einstein) finished a substantially extended work of his June paper (the so-called „Palermo paper“, received 23 July, printed 14 December, published January 1906). He spoke literally of „the postulate of relativity“. He showed that the transformations are a consequence of the Principle of Least Action and developed the properties of the Poincaré stresses. He demonstrated in more detail the group characteristics of the transformation, which he called the Lorentz group, and he showed that the combination $x^2+y^2+z^2-c^2t^2$ is invariant. While elaborating his gravitational theory, he said the Lorentz transformation is merely a rotation in four-dimensional space about the origin, by introducing $ct\sqrt{-1}$ as a fourth imaginary coordinate (contrary to Palagyi, he included the speed of light), and he already used four-vectors. He wrote that the discovery of magneto-cathode rays by Paul Ulrich Villard (1904) seems to threaten the entire theory of Lorentz, but this problem was quickly solved.[51] However, although in his philosophical writings Poincaré rejected the ideas of absolute space and time, in his physical papers he continued to refer to an (undetectable) aether. He also continued (1900b, 1904, 1906, 1908b) to describe coordinates and phenomena as local/apparent (for moving observers) and true/real (for observers at rest in the aether).[21][52] So with a few exceptions[53][54][55][56] most historians of science argue that Poincaré did not invent what is now called special relativity, although it is admitted that Poincaré anticipated much of Einstein's methods and terminology.[57][58][59][60][61][62]

Special relativity

Einstein 1905

Electrodynamics of moving bodies


Albert Einstein, 1921

On September 26, 1905 (received 30 June), Albert Einstein published his annus mirabilis paper on what is now called *special relativity*. Einstein's paper includes a fundamental new definition of space and time (all time and space coordinates in all reference frames are equal, so there is no "true" or "apparent" time) and the abolition of the aether. He identified two fundamental principles, the Principle of Relativity and the *Principle of the Constancy of Light*, which served as the axiomatic basis of his theory. To better understand Einstein's step, a summary of the situation before 1905, as it was described above, shall be given[63] (it must be remarked that Einstein was familiar with the 1895 theory of Lorentz, and "Science and Hypothesis" by Poincaré, but not their papers of 1904-1905):

> *a*) Maxwell's electrodynamics, as presented by Lorentz in 1895, was the most successful theory at this time. Here, the speed of light is constant in all directions in the stationary aether, and completely independent of the velocity of the source;
>
> *b*) The inability to find an absolute state of motion, *i.e.*, the validity of the relativity principle as the consequence of the negative results of all aether drift experiments, and effects like the moving magnet and conductor problem which only depend on relative motion;
>
> *c*) The Fizeau experiment;
>
> *d*) The aberration of light;

with the following consequences for the speed of light, and the theories known at that time:

1. The speed of light is not composed by the speed of light in vacuum and the velocity of a preferred frame of reference, by *b*. This contradicts the theory of the (nearly) stationary aether.
2. The speed of light is not composed by the speed of light in vacuum and the velocity of the light source, by *a* and *c*. This contradicts the emission theory.
3. The speed of light is not composed by the speed of light in vacuum and the velocity of an aether that would be dragged within or in the vicinity of matter, by *a, c*, and *d*. This contradicts the hypothesis of the complete aether drag.
4. The speed of light in moving media is not composed by the speed of light when the medium is at rest, and the velocity of the medium, but is determined by Fresnel's dragging coefficient, by *c*.[64]

To make the preceding theories tenable, the introduction of ad hoc hypotheses would be required. Yet in science the assumption of a conspiracy of effects which prevent the discovery of other effects is considered to be very improbable, and it would violate Occam's razor as well.[65] So Einstein refused to invent auxiliary hypotheses, and draw the direct conclusions from the facts stated above: That the relativity principle is correct and the speed of light is constant in all inertial reference frames. Because of his axiomatic method, Einstein was able to derive *all results* of his predecessors – and in addition the formulas for the relativistic Doppler effect and relativistic aberration – on a few pages, while his predecessors needed years of long, complicated work to arrive at the same mathematical formalism. Lorentz and Poincaré had also adopted these same principles, as necessary to achieve their final results, but didn't recognize that they were also sufficient, and hence that they obviated all the other assumptions (especially the stationary aether) underlying Lorentz's initial derivations.[61][66] Another reason for Einstein's rejection of the aether was probably his work on quantum physics. Einstein found out that light can also be described as a particle, so the aether as the medium for electromagnetic "waves" (which was highly important for Lorentz and Poincaré) had no place in his theoretical concepts anymore.[67]

It's notable that Einstein's paper contains no direct references to other papers. However, many historians of science like Holton,[65] Miller,[58] Stachel,[68] have tried to find out possible influences on Einstein. He stated that his thinking was influenced by the empiricist philosophers David Hume and Ernst Mach. Regarding the Relativity Principle, the moving magnet and conductor problem (possibly after reading a book of August Föppl) and the various negative aether drift experiments were important for him to accept that principle — but he denied any significant influence of the *most important* experiment: the Michelson-Morley experiment.[68] Other possible sources are Poincaré's *Science and Hypothesis*, where he described the Principle of Relativity and which was read by Einstein in 1904,[69] and the writings of Max Abraham, from whom he borrowed the terms "Maxwell-Hertz equations" and "longitudinal and transverse mass".[70]

Regarding his views on Electrodynamics and the Principle of the Constancy of Light, Einstein stated that Lorentz's theory of 1895 (or the Maxwell-Lorentz electrodynamics) and also the Fizeau experiment had considerable influence on his thinking. He said in 1909 and 1912 that he borrowed that principle from Lorentz's stationary aether (which implies validity of Maxwell's equations and the constancy of light in the aether frame), but he recognized that this principle together with the principle of relativity makes the aether useless.[71] As he wrote in 1907 and in later papers, the apparent contradiction between those principles can be solved if it is realized that Lorentz's local time is not an auxiliary quantity, but can simply be defined as *time* and is connected with signal velocity. Before Einstein, also Poincaré developed a similar physical interpretation of local time and noticed the connection to signal velocity, but contrary to Einstein he continued to argue that clocks in the aether show the true time, and moving clocks show the apparent time. Eventually, in 1953 Einstein described the advances of his theory (although Poincaré already stated in 1905 that Lorentz invariance is a general condition for any physical theory):[71]

> “There is no doubt, that the special theory of relativity, if we regard its development in retrospect, was ripe for discovery in 1905. Lorentz had already recognized that the transformations named after him are essential for the analysis of Maxwell's equations, and Poincaré deepened this insight still further. Concerning myself, I knew only Lorentz's important work of 1895 [...] but not Lorentz's later work, nor the consecutive investigations by Poincaré. In this sense my work of 1905 was independent. [..] The new feature of it was the realization of the fact that the bearing of the Lorentz transformation transcended its connection with Maxwell's equations and was concerned with the nature of space and time in general. A further new result was that the "Lorentz invariance" is a general condition for any physical theory. This was for me of particular importance because I had already previously found that Maxwell's theory did not account for the micro-structure of radiation and could therefore have no general validity. ”

Mass-energy equivalence

Already in §10 of his paper on electrodynamics, Einstein used the formula

$$E_{kin} = mc^2 \left(\frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} - 1 \right)$$

for the kinetic energy of an electron. In elaboration of this he published a paper (received 27 September, November 1905), in which Einstein showed that when a material body lost energy (either radiation or heat) of amount E, its mass decreased by the amount E/c^2. This led to the famous mass–energy equivalence formula: $E = mc^2$. Einstein considered the equivalency equation to be of paramount importance because it showed that a massive particle possesses an energy, the "rest energy", distinct from its classical kinetic and potential energies.[29] As it was shown above, many authors before Einstein arrived at similar formulas (including a 4/3-factor) for the relation of mass to energy. However, their work was focused on electromagnetic energy which (as we know today) only represents a small part of the entire energy within matter. So it was Einstein who was the first a) to ascribe this relation to all forms of energy, and b) to understand the connection of Mass-energy equivalence with the relativity principle.

Early reception

First assessments

Walter Kaufmann (1905, 1906) was probably the first who referred to Einstein's work. He compared the theories of Lorentz and Einstein, and, although he said Einstein's method is to be preferred, he argued that both theories are observationally equivalent. Therefore, he spoke of the relativity principle as the "Lorentz-Einsteinian" basic assumption.[72] Shortly afterwards, Max Planck (1906a) was the first who publicly defended the theory, and who interested his students Max von Laue and Kurd von Mosengeil for this theory. He described Einstein's theory as a "generalization" of Lorentz's theory, and to this "Lorentz-Einstein-Theory" he gave the name "relative theory", while Alfred Bucherer changed Planck's notation into the now common "theory of relativity". On the other hand, Einstein himself and many others continued to simply refer to the new method as the "relativity principle". And in an important overview article on the relativity principle (1908a), Einstein described SR as a "union of Lorentz's theory and the relativity principle", including the fundamental assumption that Lorentz's local time can be described as real time. (Yet, Poincaré's contributions were rarely mentioned in the first years after 1905.) All of those expressions (Lorentz-Einstein theory, relativity principle, relativity theory) were used by different physicists alternately in the next years.[73]

Kaufmann-Bucherer experiments

Kaufmann (1905, 1906) announced the results of his new experiments on the charge to mass ratio, i.e. the velocity dependence of mass. They represented, in his opinion, a clear refutation of the relativity principle and the Lorentz-Einstein-Theory, and a confirmation of Abraham's theory. For some years, Kaufmann's experiments represented a weighty objection against the relativity principle, although it was criticized by Planck and Adolf Bestelmeyer (1906). Following Kaufmann, other physicists like Alfred Bucherer (1908), and Günther Neumann (1914) also examined the velocity-dependence of mass, and this time it was thought that the "Lorentz-Einstein theory" and the relativity principle is confirmed, and Abraham's theory is disproved. However, it was later pointed out that the Kaufmann–Bucherer–Neumann experiments only showed a qualitative mass increase of moving electron, but they were not precise enough to distinguish between the models of Lorentz-Einstein and Abraham. So it lasted until 1940, when experiments of this kind were repeated with sufficient accuracy for confirming the Lorentz-Einstein formula.[72] However, this problem occurred only for this kind of experiments. The investigations of the fine structure of the hydrogen lines already in 1917 provided a clear confirmation of the Lorentz-Einstein formula, and the refutation of Abraham's theory.[74]

Relativistic momentum and mass

Max Planck

Planck (1906a) defined the relativistic momentum and gave the correct values for the longitudinal and transverse mass by correcting a slight mistake of the expression given by Einstein in 1905. Planck's expressions were in principle equivalent to those used by Lorentz in 1899.[75] Based on the work of Planck, the concept of relativistic mass was developed by Gilbert Newton Lewis and Richard C. Tolman (1908, 1909) by defining mass as the ratio of momentum to velocity. So the older definition of longitudinal and transverse mass, in which mass was defined as the ratio of force to acceleration, became superfluous. Finally, Tolman (1912) interpreted relativistic mass simply as *the* mass of the body.[76] However, many modern textbooks on relativity don't use the concept of relativistic mass anymore, and mass is considered as an invariant quantity.

Mass and energy

Einstein (1906) showed that the inertia of energy (mass-energy-equivalence) is a necessary and sufficient condition for the conservation of the center of mass theorem. On that occasion, he noted that the formal mathematical content of Poincaré paper on the center of mass (1900b) and his own paper were mainly the same, although the physical interpretation was different in light of relativity.[29]

Kurd von Mosengeil (1906) by extending Hasenöhrl's calculation of black-body-radiation in a cavity, derived the same expression for the additional mass of a body due to electromagnetic radiation as Hasenöhrl. Hasenöhrl's idea was that the mass of bodies included a contribution from the electromagnetic field, he imagined a body as a cavity containing light. His relationship between mass and energy, like all other pre-Einstein ones, contained incorrect numerical prefactors (see Electromagnetic mass). Eventually Planck (1907) derived the mass-energy-equivalence in general within the framework of special relativity, including the binding forces within matter. He acknowledged the priority of Einstein's 1905 work on $E = mc^2$, but Planck judged his own approach as more general than Einstein's.[77]

Experiments by Fizeau and Sagnac

As it was explained above, already in 1895 Lorentz succeeded in deriving Fresnel's dragging coefficient (to first order of v/c) and the Fizeau experiment by using the electromagnetic theory and the concept of local time. After first attempts by Jakob Laub (1907) to create a relativistic "optics of moving bodies", it was Max von Laue (1907) who derived the coefficient for terms of all orders by using the colinear case of the relativistic velocity addition law. In addition, Laue's calculation was much simpler than the complicated methods used by Lorentz.[22]

In 1911 Laue also discussed a situation where on a platform a beam of light is split and the two beams are made to follow a trajectory in opposite directions. On return to the point of entry the light is allowed to exit the platform in such a way that an interference pattern is obtained. Laue calculated a displacement of the interference pattern if the platform is in rotation – because the speed of light is independent of the velocity of the source, so one beam has covered less distance than the other beam. An experiment of this kind was performed by Georges Sagnac in 1913, who actually measured a displacement of the interference pattern (Sagnac effect). While Sagnac himself concluded that his theory confirmed the theory of an aether at rest, Laue's earlier calculation showed that it is compatible with special relativity as well because in *both* theories the speed of light is independent of the velocity of the source. This effect can be understood as the electromagnetic counterpart of the mechanics of rotation, for example in analogy to a Foucault pendulum[78] [Already in 1909–11, Franz Harress (1912) performed an experiment which can be considered as a synthesis of the experiments of Fizeau and Sagnac. He tried to measure the dragging coefficient within glass. Contrary to Fizeau he used a rotating device so he found the same effect as Sagnac. While Harress himself misunderstood the meaning of the result, it was shown by Laue that the theoretical explanation of Harress' experiment is in accordance with the Sagnac effect.[79]] Eventually, the Michelson–Gale–Pearson experiment (1925, a variation of the Sagnac experiment) indicated the angular velocity of the Earth itself in accordance with special relativity and a resting aether.

Relativity of simultaneity

The first derivations of relativity of simultaneity by synchronization with light signals were also simplified.[80] Daniel Frost Comstock (1910) placed an observer in the middle between two clocks A and B. From this observer a signal is sent to both clocks, and in the frame in which A and B are at rest, they synchronously start to run. But from the perspective of a system in which A and B are moving, clock B is first set in motion, and then comes clock A – so the clocks are not synchronized. Also Einstein (1917) created a model with an observer in the middle between A and B. However, in his description two signals are sent *from* A and B to the observer. From the perspective of the frame, in which A and B are at rest, the signals are sent at the same time and the observer "*is hastening towards the beam of light coming from B, whilst he is riding on ahead of the beam of light coming from A. Hence the observer will see the beam of light emitted from B earlier than he will see that emitted from A. Observers who take the railway train as their reference-body must therefore come to the conclusion that the lightning flash B took place earlier than the lightning flash A.*"

Spacetime physics

Minkowski's spacetime

Poincaré's attempt of a four-dimensional reformulation of the new mechanics was not continued by himself,[51] so it was Hermann Minkowski (1907), who worked out the consequences of that notion (other contributions were made by Roberto Marcolongo (1906) and Richard Hargreaves (1908)[81]). This was based on the work of many mathematicians of the 19th century like Arthur Cayley, Felix Klein, or William Kingdon Clifford, who contributed to group theory, invariant theory and projective geometry.[82] Using similar methods, Minkowski succeeded in formulating a geometrical interpretation of the Lorentz transformation. He completed, for example, the concept of four vectors; he created the Minkowski diagram for the depiction of space-time; he was the first to use expressions like world line, proper time, Lorentz invariance/covariance, etc.; and most notably he presented a four-dimensional formulation of electrodynamics. Similar to Poincaré he tried to formulate a Lorentz-invariant law of gravity, but that work was subsequently superseded by Einstein's elaborations on gravitation.


Hermann Minkowski

In 1907 Minkowski named four predecessors who contributed to the formulation of the relativity principle: Lorentz, Einstein, Poincaré and Planck. And in his famous lecture Space and Time (1908) he mentioned Voigt, Lorentz and Einstein. Minkowski himself considered Einstein's theory as a generalization of Lorentz's and credited Einstein for completely stating the relativity of time, but he criticized his predecessors for not fully developing the relativity of space. However, modern historians of science argue that Minkowski's claim for priority was unjustified, because

Minkowski (like Wien or Abraham) adhered to the electromagnetic world-picture and apparently didn't fully understand the difference between Lorentz's electron theory and Einstein's kinematics.[83][84] In 1908, Einstein and Laub rejected the four-dimensional electrodynamics of Minkowski as too complicated and published a "more elementary", non-four-dimensional derivation of the basic-equations for moving bodies. But it was Minkowski's formalism which a) showed that special relativity is a complete and consistent theory, and b) served as a basis for further development of relativity.[81] Eventually, Einstein (1912) agreed on the importance of Minkowski's spacetime formalism and used it for his work on the foundations of general relativity.

Today special relativity is seen as an application of linear algebra, but at the time special relativity was being developed the field of linear algebra was still in its infancy. There were no textbooks on linear algebra as modern vector space and transformation theory, and the matrix notation of Arthur Cayley (that unifies the subject) had not yet come into widespread use. In retrospect, we can see that the Lorentz transformations are simply hyperbolic rotations, as explicitly noted by Minkowski.

Vector notation and closed systems

Minkowski's space-time formalism was quickly accepted and further developed.[84] For example, Arnold Sommerfeld (1910) replaced Minkowski's matrix notation by an elegant vector notation and coined the terms "four vector" and "six vector". He also introduced a trigonometric formulation of the relativistic velocity addition rule, which according to Sommerfeld, removes much of the strangeness of that concept. Other important contributions were made by Laue (1911, 1913), who used the spacetime formalism to create a relativistic theory of deformable bodies and an elementary particle theory.[85][86] He extended Minkowski's expressions for electromagnetic processes to all possible forces and thereby clarified the concept of mass-energy-equivalence. Laue also showed that non-electrical forces are needed to ensure the proper Lorentz transformation properties, and for the stability of matter – he could show that the "Poincaré stresses" (as mentioned above) are a natural consequence of relativity theory so that the electron be a closed system.

Lorentz transformation without second postulate

There were some attempts to derive the Lorentz transformation without the postulate of the constancy of the speed of light. Vladimir Ignatowski (1910) for example used for this purpose a) the principle of relativity, b) and homogeneity and isotropy of space c) the requirement of reciprocity. Philipp Frank and Hermann Rothe (1911) argued that this derivation is incomplete and needs additional assumptions. Their own calculation was based on the assumptions that a) the Lorentz transformation forms a homogeneous linear group, b) when changing frames, only the sign of the relative speed changes, c) length contraction solely depends on the relative speed. However, according to Pauli and Miller such models were insufficient to identify the invariant speed in their transformation with the speed of light — for example, Ignatowski was forced to recourse to electrodynamics to include the speed of light. So Pauli and others argued that both postulates are needed to derive the Lorentz transformation.[87][88] However, until today, others continued the attempts to derive special relativity without the light postulate.

Non-euclidean formulations without imaginary time coordinate

It was noted by Minkowski (1907) that his space-time formalism represents a "four-dimensional non-euclidean manifold", but in order to emphasize the formal similarity to the more familiar Euclidean geometry, Minkowski noted that the time coordinate could be treated as imaginary. This was just a way of representing a non-Euclidean metric while emphasizing the formal similarity to a Euclidean metric. However, many subsequent writers [*citation needed*]have dispensed with the imaginary time coordinate, and simply written the metric in explicitly non-Euclidean form (i.e., with a negative signature), since it makes no difference to the content or results of the equations. It merely affects (slightly) their appearance. Sommerfeld (1910) gave a trigonometric formulation of velocities, and Vladimir Varićak (1912) emphasized the similarity of this formulation to (Bolyai-Lobachevskian) hyperbolic geometry and tried to reformulate relativity using that non-euclidean geometry. Alfred Robb (1911) introduced the concept of

Rapidity as a hyperbolic angle to characterize frame velocity. Edwin Bidwell Wilson and Gilbert N. Lewis (1912) introduced a vector notation for spacetime. Émile Borel (1913) derived the kinematic basis of Thomas precession.[89] Different authors [*citation needed*] have used the phrase hyperbolic plane to refer both to (Bolyai-Lobachevskian) hyperbolic geometry and Minkowski geometry but these are two different geometries. Space-time is described by Minkowski space, but the velocity space is described by hyperbolic geometry. In particular the hyperboloid model was identified with velocities by Minkowski (1908). Today one still finds texts on special relativity that make use of an imaginary time coordinate, but most have adopted real-valued coordinates and a metric with negative signature. (The implications of the two different formalisms in the context of general relativity - as in the recent work of Hawking [*citation needed*]- are beyond the scope of this article.)

Time dilation and twin paradox

Einstein (1907a) proposed a method for detecting the transverse Doppler effect as a direct consequence of time dilation. And in fact, that effect was measured in 1938 by Herbert E. Ives and G. R. Stilwell (Ives–Stilwell experiment).[90] And Lewis and Tolman (1909) described the reciprocity of time dilation by using two light clocks A and B, traveling with a certain relative velocity to each other. The clocks consist of two plane mirrors parallel to one another and to the line of motion. Between the mirrors a light signal is bouncing, and for the observer resting in the same reference frame as A, the period of clock A is the distance between the mirrors divided by the speed of light. But if the observer looks at clock B, he sees that within that clock the signal traces out a longer, angled path, thus clock B is slower than A. However, for the observer moving alongside with B the situation is completely in reverse: Clock B is faster and A is slower. Also Lorentz (1910–1912) discussed the reciprocity of time dilation and analyzed a clock "paradox", which apparently occurs as a consequence of the reciprocity of time dilation. Lorentz showed that there is no paradox if one considers that in one system only one clock is used, while in the other system two clocks are necessary. So the relativity of simultaneity has to be considered as well.

A similar situation was created by Paul Langevin in 1911 with what was later called the "twin paradox", where he replaced the clocks by persons (Langevin never used the word "twins" but his description contained all other features of the paradox). Langevin solved the paradox by alluding to the fact that one twin accelerates and changes direction, so Langevin could show that the symmetry is broken and the accelerated twin is younger. However, Langevin himself interpreted this as a hint to the existence of an aether. Although Langevin's explanation is used in principle until today, his deductions regarding the aether were not accepted. Laue (1913) pointed out that the acceleration can be made arbitrarily small in relation to the inertial motion of the twin. So it is much more important that one twin travels within two inertial frames during his journey, while the other twin remains in one frame. Laue was also the first to visualize the situation using Minkowski spacetime-formalism – he demonstrated how the world lines of inertially moving bodies maximize the proper time elapsed between two events.[91]

Acceleration

Einstein (1908) tried – as a preliminary in the framework of special relativity – also to include accelerated frames within the relativity principle. In the course of this attempt he recognized that for any single moment of acceleration of a body one can define an inertial reference frame in which the accelerated body is temporarily at rest. It follows that in accelerated frames defined in this way, the application of the constancy of the speed of light to define simultaneity is restricted to small localities. However, the equivalence principle that was used by Einstein in the course of that investigation, which expresses the equality of inertial and gravitational mass and the equivalence of accelerated frames and homogeneous gravitational fields, transcended the limits of special relativity and resulted in the formulation of general relativity.[92]

Nearly simultaneously with Einstein, also Minkowski (1908) considered the special case of uniform accelerations within the framework of his space-time formalism. He recognized that the world-line of such an accelerated body corresponds to a hyperbola. This notion was further developed by Born (1909) and Sommerfeld (1910), with Born introducing the expression "hyperbolic motion". He noted that uniform acceleration can be used as an approximation for any form of acceleration within special relativity.[93] In addition, Harry Bateman and Ebenezer Cunningham (1910) showed that Maxwell's equations are invariant under a much wider group of transformation than the Lorentz-group, i.e., the so-called "conformal transformations". Under those transformations the equations preserve their form for some types of accelerated motions.[94] A general covariant formulation of electrodynamics in Minkowski space was eventually given by Friedrich Kottler (1912), whereby his formulation is also valid for general relativity.[95] Concerning the further development of the description of accelerated motion in special relativity, the works by Langevin and others for rotating frames (Born coordinates), and by Wolfgang Rindler and others for uniform accelerated frames (Rindler coordinates) must be mentioned.[96]

Rigid bodies and Ehrenfest paradox

Einstein (1907b) discussed the question of whether, in rigid bodies, as well as in all other cases, the velocity of information can exceed the speed of light, and explained that information could be transmitted under these circumstances into the past, thus causality would be violated. Since this contravenes radically against every experience, superluminal velocities are thought impossible. He added that a dynamics of the rigid body must be created in the framework of SR. Eventually, Max Born (1909) in the course of his above mentioned work concerning accelerated motion, tried to include the concept of rigid bodies into SR. However, Paul Ehrenfest (1909) showed that Born's concept lead the so-called Ehrenfest paradox, in which, due to length contraction, the circumference of a rotating disk is shortened while the radius stays the same. This question was also considered by Gustav Herglotz (1910), Fritz Noether (1910), and von Laue (1911). It was recognized by Laue that the classic concept is not applicable in SR since a "rigid" body possesses infinitely many Degrees of freedom. Yet, while Born's definition was not applicable on rigid bodies, it was very useful in describing rigid *motions* of bodies.[97] In connection to the Ehrenfest paradox, it was also discussed (by Vladimir Varićak and others) whether length contraction is "real" or "apparent", and whether there is a difference between the dynamic contraction of Lorentz and the kinematic contraction of Einstein. However, it was rather a dispute over words because, as Einstein said, the kinematic length contraction is "apparent" for an co-moving observer, but for an observer at rest it is "real" and the consequences are measurable.[98]

Acceptance of special relativity

Eventually, around 1911 most mathematicians and theoretical physicists accepted the results of special relativity. For example, already Planck (1909) compared the implications of the modern relativity principle — especially Einstein's relativity of time — with the revolution by the Copernican system.[99] As a result, the fundamental difference between the dynamic approach of Lorentz and the kinematic one of Einstein was pointed out, and the term "Lorentz-Einstein-Theory" wasn't used anymore. Only a few theoretical physicists like Lorentz, Poincaré, Abraham or Langevin, still believed in the existence of an aether in any form.[100] Another important reason for accepting special relativity was the extension of Minkowski's space-time formalism around 1910–1913.[84] So in 1912 Wilhelm Wien recommended both Lorentz and Einstein for the Nobel Prize in Physics – even though this prize was never awarded for special relativity. After formulating GR, Einstein in 1915, for the first time, used the expression "special theory of relativity" to distinguish between the theories.

Relativistic theories

Gravitation

The first attempt to formulate a relativistic theory of gravitation was undertaken by Poincaré (1905). He tried to modify Newton's law of gravitation so that it assumes a Lorentz-covariant form. He noted that there were many possibilities for a relativistic law, and he discussed two of them. It was shown by Poincaré that the argument of Pierre-Simon Laplace, who argued that the speed of gravity is many times faster than the speed of light, is not valid within a relativistic theory. That is, in a relativistic theory of gravitation, planetary orbits are stable even when the speed of gravity is equal to that of light. Similar models as that of Poincaré were discussed by Minkowski (1907b) and Sommerfeld (1910). However, it was shown by Abraham (1912) that those models belong to the class of "vector theories" of gravitation. The fundamental defect of those theories is that they implicitly contain a negative value for the gravitational energy in the vicinity of matter, which would violate the energy principle. As an alternative, Abraham (1912) and Gustav Mie (1913) proposed different "scalar theories" of gravitation. While Mie never formulated his theory in a consistent way, Abraham completely gave up the concept of Lorentz-covariance (even locally), and therefore it was irreconcilable with relativity.

In addition, all of those models violated the equivalence principle, and Einstein argued that it is impossible to formulate a theory which is both Lorentz-covariant and satisfies the equivalence principle. However, Gunnar Nordström (1912, 1913) was able to create a model which fulfilled both conditions. This was achieved by making both the gravitational and the inertial mass dependent on the gravitational potential. Nordström's theory of gravitation was remarkable because it was shown by Einstein and Adriaan Fokker (1914), that in this model gravitation can be completely described in terms of space-time curvature. Although Nordström's theory is without contradiction, from Einstein's point of view a fundamental problem persisted: It doesn't fulfill the important condition of general covariance, as in this theory preferred frames of referenced can still be formulated. So contrary to those "scalar theories", Einstein (1911–1915) developed a "tensor theory" (i.e. general relativity), which fulfills both the equivalence principle and general covariance. As a consequence, the notion of a complete "special relativistic" theory of gravitation had to be given up, as in general relativity the constancy of light speed (and Lorentz covariance) is only locally valid. The decision between those models was brought about by Einstein, when he was able to exactly derive the perihelion precession of Mercury, while the other theories gave erroneous results. In addition, Einstein's theory was the only theory which gave the correct value for the deflection of light near the sun.[101][102]

Quantum field theory

The need to put together relativity and quantum mechanics was one of the major motivations in the development of quantum field theory. Pascual Jordan and Wolfgang Pauli showed in 1928 that quantum fields could be made to be relativistic, and Paul Dirac produced the Dirac equation for electrons, and in so doing predicted the existence of antimatter.[103]

Many other domains have since been reformulated with relativistic treatments: relativistic thermodynamics, relativistic statistical mechanics, relativistic hydrodynamics, relativistic quantum chemistry, relativistic heat conduction, etc.

Experimental evidence

Important early experiments confirming special relativity as mentioned above were the Fizeau experiment, the Michelson–Morley experiment, the Kaufmann–Bucherer–Neumann experiments, the Trouton–Noble experiment, the experiments of Rayleigh and Brace, and the Trouton–Rankine experiment.

In the 1920s, a series of Michelson-Morley type experiments were conducted, confirming relativity to even higher precision than the original experiment. Another type of interferometer experiment was the Kennedy–Thorndike experiment in 1932, by which the independence of the speed of light on the apparatus' velocity was confirmed. Also time dilation was directly measured in the Ives–Stilwell experiment in 1938 and by measuring the decay rates of moving particles in 1940. All of those experiments have been repeated several times with increased precision. In addition, that the speed of light is unreachable for massive bodies was measured in many tests of relativistic energy and momentum. Therefore, knowledge of those relativistic effects is required in the construction of particle accelerators.

Many other tests of special relativity have been conducted, testing possible violations of Lorentz invariance in some variants of quantum gravity. However, no sign of anisotropy of the speed of light has been found even at the 10^{-17}

level, and some experiments even ruled out Lorentz violations at the 10^{-40} level, see Modern searches for Lorentz violation.

Priority

Some claim that Poincaré (and Lorentz), not Einstein, are the true founders of special relativity. For more see the article on relativity priority dispute.

Criticisms

Some criticized Special Relativity for various reasons, such as lack of empirical evidence, internal inconsistencies, rejection of mathematical physics *per se*, or philosophical reasons. Although there still are critics of relativity outside the scientific mainstream, the overwhelming majority of scientists agree that Special Relativity has been verified in many different ways and there are no inconsistencies within the theory.

References

Primary sources

- Abraham, Max (1902), "Dynamik des Electrons", *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse*: 20–41
- Abraham, Max (1903), "Prinzipien der Dynamik des Elektrons", *Annalen der Physik* **315** (1): 105–179, Bibcode:1902AnP...315..105A [104], doi:10.1002/andp.19023150105 [105]
- Abraham, Max (1904), "The Fundamental Hypotheses of the Theory of Electrons", *Physikalische Zeitschrift* **5**: 576–579
- Abraham, Max (1914), "Neuere Gravitationstheorien" [106], *Jahrbuch für Radioaktivität und Elektronik* **11** (4): 470–520.
- Alväger, Farley, Kjellmann, Walle (1964), "Test of the second postulate of special relativity in the GeV region", *Phys. Rev. Letters* **12** (3): 260–262, Bibcode:1964PhL....12..260A [107], doi:10.1016/0031-9163(64)91095-9 [108]
- Bartoli, Adolfo (1876/1884), "Il calorico raggiante e il secondo principio di termodynamica" [109], *Nuovo Cimento* **15**: 196–202
- Bateman, Harry (1909/10), "The Transformation of the Electrodynamical Equations", *Proceedings of the London Mathematical Society* **8** (1): 223–264, doi:10.1112/plms/s2-8.1.223 [110].
- Borel, Émile (1913), "La théorie de la relativité et la cinématique" [111], *Comptes Rendus des Séances de l'Académie des Sciences* **156**: 215–218
- Borel, Émile (1913), "La cinématique dans la théorie de la relativité" [112], *Comptes Rendus des Séances de l'Académie des Sciences* **157**: 703–705
- Born, Max (1909), "The Theory of the Rigid Electron in the Kinematics of the Principle of Relativity", *Annalen der Physik* **335** (11): 1–56, Bibcode:1909AnP...335....1B [113], doi:10.1002/andp.19093351102 [114]
- Brecher, Kenneth (1977), "Is the Speed of Light Independent of the Velocity of the Source?", *Phys. Rev. Letters* **39** (17): 1051–1054, Bibcode:1977PhRvL..39.1051B [115], doi:10.1103/PhysRevLett.39.1051 [116]
- Bucherer, A. H. (1903), "Über den Einfluß der Erdbewegung auf die Intensität des Lichtes", *Annalen der Physik* **316** (6): 270–283, Bibcode:1903AnP...316..270B [117], doi:10.1002/andp.19033160604 [118]
- Bucherer, A. H. (1908), "Measurements of Becquerel rays. The Experimental Confirmation of the Lorentz-Einstein Theory", *Physikalische Zeitschrift* **9** (22): 755–762
- Cohn, Emil (1901), "Über die Gleichungen der Electrodynamik für bewegte Körper", *Archives néerlandaises des sciences exactes et naturelles* **5**: 516–523

- Cohn, Emil (1904), "On the Electrodynamics of Moving Systems I", *Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften*, 1904/2 (40): 1294–1303
- Cohn, Emil (1904), "On the Electrodynamics of Moving Systems II", *Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften*, 1904/2 (43): 1404–1416
- Comstock, Daniel Frost (1910), "The Principle of Relativity", *Science* **31** (803): 767–772, Bibcode:1910Sci....31..767C [119], doi:10.1126/science.31.803.767 [120], PMID 17758464 [121]
- Cunningham, Ebenezer (1909/10), "The principle of Relativity in Electrodynamics and an Extension Thereof", *Proceedings of the London Mathematical Society* **8** (1): 77–98, doi:10.1112/plms/s2-8.1.77 [122].
- De Sitter, Willem (1913), "A proof of the constancy of the velocity of light", *Proceedings of the Royal Netherlands Academy of Arts and Sciences* **15** (2): 1297–1298
- De Sitter, Willem (1913), "On the constancy of the velocity of light", *Proceedings of the Royal Netherlands Academy of Arts and Sciences* **16** (1): 395–396
- Ehrenfest, Paul (1909), "Uniform Rotation of Rigid Bodies and the Theory of Relativity", *Physikalische Zeitschrift* **10**: 918
- Einstein, Albert (1905a), "Zur Elektrodynamik bewegter Körper", *Annalen der Physik* **322** (10): 891–921, Bibcode:1905AnP...322..891E [122], doi:10.1002/andp.19053221004 [123]. See also: English translation [123].
- Einstein, Albert (1905b), "Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig?", *Annalen der Physik* **323** (13): 639–643, Bibcode:1905AnP...323..639E [124], doi:10.1002/andp.19053231314 [125]. See also the English translation [124].
- Einstein, Albert (1906), "Das Prinzip von der Erhaltung der Schwerpunktsbewegung und die Trägheit der Energie", *Annalen der Physik* **325** (8): 627–633, Bibcode:1906AnP...325..627E [125], doi:10.1002/andp.19063250814 [126]
- Einstein, Albert (1907), "Über die vom Relativitätsprinzip geforderte Trägheit der Energie", *Annalen der Physik* **328** (7): 371–384, Bibcode:1907AnP...328..371E [127], doi:10.1002/andp.19073280713 [128]
- Einstein, Albert (1908a), "Über das Relativitätsprinzip und die aus demselben gezogenen Folgerungen", *Jahrbuch der Radioaktivität und Elektronik* **4**: 411–462, Bibcode:1908JRE.....4..411E [129]
- Einstein, Albert & Laub, Jakob (1908b), "Über die elektromagnetischen Grundgleichungen für bewegte Körper" [130], *Annalen der Physik* **331** (8): 532–540, Bibcode:1908AnP...331..532E [131], doi:10.1002/andp.19083310806 [132]
- Einstein, Albert (1909), "The Development of Our Views on the Composition and Essence of Radiation", *Physikalische Zeitschrift* **10** (22): 817–825
- Einstein, Albert (1912), "Relativität und Gravitation. Erwiderung auf eine Bemerkung von M. Abraham" [133], *Annalen der Physik* **38** (10): 1059–1064, Bibcode:1912AnP...343.1059E [134], doi:10.1002/andp.19123431014 [135]
- Einstein A. (1916), *Relativity: The Special and General Theory*, Springery
- Einstein, Albert (1922), *Ether and the Theory of Relativity*, Methuen & Co.
- FitzGerald, George Francis (1889), "The Ether and the Earth's Atmosphere", *Science* **13** (328): 390, Bibcode:1889Sci....13..390F [136], doi:10.1126/science.ns-13.328.390 [137], PMID 17819387 [138]
- Fizeau, H. (1851). "The Hypotheses Relating to the Luminous Aether, and an Experiment which Appears to Demonstrate that the Motion of Bodies Alters the Velocity with which Light Propagates itself in their Interior". *Philosophical Magazine* **2**: 568–573.
- Frank, Philipp & Rothe, Hermann (1910), "Über die Transformation der Raum-Zeitkoordinaten von ruhenden auf bewegte Systeme" [139], *Annalen der Physik* **339** (5): 825–855, Bibcode:1911AnP...339..825F [140],

doi:10.1002/andp.19113390502 [141]

- Fresnel, Augustin (1816), "Sur la diffraction de la lumière" [142], *Annales de chimie et de physique* **2**: 239–281 Wikipedia:Link rot
- Hasenöhrl, Friedrich (1904), "On the Theory of Radiation in Moving Bodies", *Annalen der Physik* **320** (12): 344–370, Bibcode:1904AnP...320..344H [143], doi:10.1002/andp.19043201206 [144]
- Hasenöhrl, Friedrich (1905), "On the Theory of Radiation in Moving Bodies. Correction", *Annalen der Physik* **321** (3): 589–592, Bibcode:1905AnP...321..589H [145], doi:10.1002/andp.19053210312 [146]
- Heaviside, Oliver (1888/1894), "Electromagnetic waves, the propagation of potential, and the electromagnetic effects of a moving charge", *Electrical papers* **2**, pp. 490–499
- Heaviside, Oliver (1889), "On the Electromagnetic Effects due to the Motion of Electrification through a Dielectric", *Philosophical Magazine*, 5 **27** (167): 324–339
- Herglotz, Gustav (1909), "On bodies that are to be designated as "rigid" from the standpoint of the relativity principle", *Annalen der Physik* **336** (2): 393–415
- Hertz, Heinrich (1890a), "Über die Grundgleichungen der Elektrodynamik für ruhende Körper", *Annalen der Physik* **276** (8): 577, Bibcode:1890AnP...276..577H [147], doi:10.1002/andp.18902760803 [148]
- Hertz, Heinrich (1890b), "Über die Grundgleichungen der Elektrodynamik für bewegte Körper", *Annalen der Physik* **277** (11): 369–399, Bibcode:1890AnP...277..369H [149], doi:10.1002/andp.18902771102 [150]
- Ignatowsky, W. v. (1910). "Some General Remarks on the Relativity Principle". *Physikalische Zeitschrift* **11**: 972–976.
- Ignatowsky, W. v. (1911). "Das Relativitätsprinzip". *Archiv der Mathematik und Physik*. 17, 18: 1–24, 17–40.
- Kaufmann, Walter (1902), "The Electromagnetic Mass of the Electron", *Physikalische Zeitschrift* **4** (1b): 54–56
- Kaufmann, Walter (1905), "On the Constitution of the Electron", *Sitzungsberichte der Königlich Preußische Akademie der Wissenschaften* **45**: 949–956
- Kaufmann, Walter (1906), "On the Constitution of the Electron", *Annalen der Physik* **324** (3): 487–553, Bibcode:1906AnP...324..487K [151], doi:10.1002/andp.19063240303 [152]
- Lange, Ludwig (1885), "Ueber die wissenschaftliche Fassung des Galileischen Beharrungsgesetzes" [153], *Philosophische Studien* **2**: 266–297
- Langevin, Paul (1904/1908), "The Relations of Physics of Electrons to Other Branches of Science", *International Congress of Arts and Science* **7**: 121–156
- Langevin, Paul (1905), "Sur l'impossibilité physique de mettre en évidence le mouvement de translation de la Terre", *Comptes Rendus des Séances de l'Académie des Sciences* **140**: 1171–1173
- Langevin, P. (1911), "The evolution of space and time" [154], *Scientia* **X**: 31–54 (translated by J. B. Sykes, 1973).
- Larmor, Joseph (1897), "On a Dynamical Theory of the Electric and Luminiferous Medium, Part 3, Relations with material media", *Philosophical transactions of the Royal society of London* **190**: 205–300, Bibcode:1897RSPTA.190..205L [155], doi:10.1098/rsta.1897.0020 [156]
- Larmor, Joseph (1900), *Aether and Matter*, Cambridge University Press
- Laub, Jakob (1907), "Zur Optik der bewegten Körper", *Annalen der Physik* **328** (9): 738–744, Bibcode:1907AnP...328..738L [157], doi:10.1002/andp.19073280910 [158]
- Laue, Max von (1907), "The Entrainment of Light by Moving Bodies According to the Principle of Relativity", *Annalen der Physik* **328** (10): 989–990, Bibcode:1907AnP...328..989L [159], doi:10.1002/andp.19073281015 [160]
- Laue, Max von (1911a), *Das Relativitätsprinzip* [161] *at the Internet Archive*, Braunschweig: Vieweg
- Laue, Max von (1911b), "On the Discussion Concerning Rigid Bodies in the Theory of Relativity", *Physikalische Zeitschrift* **12**: 85–87

- Laue, Max von (1911c), "On an Experiment on the Optics of Moving Bodie", *Münchener Sitzungsberichte* **1911**: 405–412
- Laue, Max von (1913), *Das Relativitätsprinzip* (2 ed.), Braunschweig: Vieweg
- Lewis, Gilbert N. (1908), "A revision of the Fundamental Laws of Matter and Energy", *Philosophical Magazine* **16**: 705–717
- Lewis, Gilbert N. & Tolman, Richard C. (1909), "The Principle of Relativity, and Non-Newtonian Mechanics", *Proceedings of the American Academy of Arts and Sciences* **44**: 709–726
- Lewis, Gilbert N. & Wilson, Edwin B. (1912), "*The Space-time Manifold of Relativity. The Non-Euclidean Geometry of Mechanics and Electromagnetics* [162] at the Internet Archive", *Proceedings of the American Academy of Arts and Sciences* **48**: 387–507
- Lorentz, Hendrik Antoon (1886), "De l'influence du mouvement de la terre sur les phénomènes lumineux", *Archives néerlandaises des sciences exactes et naturelles* **21**: 103–176
- Lorentz, Hendrik Antoon (1892a), "*La Théorie electromagnétique de Maxwell et son application aux corps mouvants* [163] at the Internet Archive", *Archives néerlandaises des sciences exactes et naturelles* **25**: 363–552
- Lorentz, Hendrik Antoon (1892b), "The Relative Motion of the Earth and the Aether", *Zittingsverlag Akad. V. Wet.* **1**: 74–79
- Lorentz, Hendrik Antoon (1895), *Attempt of a Theory of Electrical and Optical Phenomena in Moving Bodies*, Leiden: E.J. Brill
- Lorentz, Hendrik Antoon (1899), "Simplified Theory of Electrical and Optical Phenomena in Moving Systems", *Proceedings of the Royal Netherlands Academy of Arts and Sciences* **1**: 427–442
- Lorentz, Hendrik Antoon (1900), "Considerations on Gravitation", *Proceedings of the Royal Netherlands Academy of Arts and Sciences* **2**: 559–574
- Lorentz, Hendrik Antoon (1904a), "Weiterbildung der Maxwellschen Theorie. Elektronentheorie." [164], *Encyclopädie der mathematischen Wissenschaften* **5** (2): 145–288
- Lorentz, Hendrik Antoon (1904b), "Electromagnetic phenomena in a system moving with any velocity smaller than that of light", *Proceedings of the Royal Netherlands Academy of Arts and Sciences* **6**: 809–831
- Lorentz, Hendrik Antoon (1910/1931), *Lecture on theoretical physics, Vol.3*, London: MacMillan
- Lorentz, Hendrik Antoon & Einstein, Albert & Minkowski, Hermann (1913), *Das Relativitätsprinzip. Eine Sammlung von Abhandlungen.* [165] *at the Internet Archive*, Leipzig & Berlin: B.G. Teubner
- Lorentz, Hendrik Antoon (1914), *Das Relativitätsprinzip. Drei Vorlesungen gehalten in Teylers Stiftung zu Haarlem*, Leipzig and Berlin: B.G. Teubner
- Lorentz, Hendrik Antoon (1914), "La Gravitation" [166], *Scientia* **16**: 28–59
- Lorentz, Hendrik Antoon (1916), *The theory of electrons and its applications to the phenomena of light and radiant heat* [167] *at the Internet Archive*, Leipzig & Berlin: B.G. Teubner
- Lorentz, Hendrik Antoon (1921), "Two Papers of Henri Poincaré on Mathematical Physics", *Acta Mathematica* **38** (1): 293–308, doi:10.1007/BF02392073 [168];
- Lorentz, Hendrik Antoon; Lorentz, H. A.; Miller, D. C.; Kennedy, R. J.; Hedrick, E. R.; Epstein, P. S. (1928), "Conference on the Michelson-Morley Experiment", *The Astrophysical Journal* **68**: 345–351, Bibcode:1928ApJ....68..341M [169], doi:10.1086/143148 [170]
- Mach, Ernst (1883/1912), *Die Mechanik in ihrer Entwicklung* [171], Leipzig: Brockhaus
- Maxwell, James Clerk (1864), "A Dynamical Theory of the Electromagnetic Field", *Philosophical Transactions of the Royal Society of London* **155**: 459–512, Bibcode:1865RSPT..155..459C [172], doi:10.1098/rstl.1865.0008 [173]

- Maxwell, James Clerk (1873), "§ 792", *A Treatise on electricity and magnetism* [174] *at the Internet Archive* **2**, London: Macmillan & Co., p. 391
- Michelson, Albert Abraham (1881), "The Relative Motion of the Earth and the Luminiferous Ether", *American Journal of Science* **22**: 120–129
- Michelson, Albert Abraham & Morley, Edward Williams (1886), "Influence of Motion of the Medium on the Velocity of Light", *American Journal of Science* **31**: 377–386
- Michelson, Albert Abraham & Morley, Edward Williams (1887), "On the Relative Motion of the Earth and the Luminiferous Ether", *American Journal of Science* **34**: 333–345
- Michelson, Albert Abraham & Gale, Henry G. (1925), "The Effect of the Earth's Rotation on the Velocity of Light", *The Astrophysical Journal* **61**: 140–145, Bibcode:1925ApJ....61..140M [175], doi:10.1086/142879 [176]
- Minkowski, Hermann (1907/1915), "Das Relativitätsprinzip", *Annalen der Physik* **352** (15): 927–938, Bibcode:1915AnP...352..927M [177], doi:10.1002/andp.19153521505 [178]
- Minkowski, Hermann (1908), "The Fundamental Equations for Electromagnetic Processes in Moving Bodies", *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse*: 53–111 (English translation in 1920 by Meghnad Saha.
- Minkowski, Hermann (1909), "Raum und Zeit", *Physikalische Zeitschrift* **10**: 75–88
  - Various English translations on Wikisource: Space and Time
- Mosengeil, Kurd von (1907), "Theorie der stationären Strahlung in einem gleichförmig bewegten Hohlraum", *Annalen der Physik* **327** (5): 867–904, Bibcode:1907AnP...327..867V [179], doi:10.1002/andp.19073270504 [180]
- Neumann, Carl (1870), *Ueber die Principien der Galilei-Newtonschen Theorie* [181] *at the Internet Archive*, Leipzig: B.G. Teubner
- Neumann, Günther (1914), "Die träge Masse schnell bewegter Elektronen" [182], *Annalen der Physik* **350** (20): 529–579, Bibcode:1914AnP...350..529N [183], doi:10.1002/andp.19143502005 [184]
- Nordström, Gunnar (1913), "Zur Theorie der Gravitation vom Standpunkt des Relativitätsprinzips" [185], *Annalen der Physik* **347** (13): 533–554, Bibcode:1913AnP...347..533N [186], doi:10.1002/andp.19133471303 [187].
- Palagyi, Menyhért (1901), *Neue Theorie des Raumes und der Zeit*, Leipzig: Wilhelm Engelmann
- Planck, Max (1906a), "The Principle of Relativity and the Fundamental Equations of Mechanics", *Verhandlungen Deutsche Physikalische Gesellschaft* **8**: 136–141
- Planck, Max (1906b), "The Measurements of Kaufmann on the Deflectability of β-Rays in their Importance for the Dynamics of the Electrons", *Physikalische Zeitschrift* **7**: 753–761
- Planck, Max (1907), "On the Dynamics of Moving Systems", *Sitzungsberichte der Königlich-Preussischen Akademie der Wissenschaften, Berlin*, Erster, Halbband (29): 542–570
- Planck, Max (1908), "Notes on the Principle of Action and Reaction in General Dynamics", *Physikalische Zeitschrift* **9** (23): 828–830
- Planck, Max (1909/1915), "General Dynamics. Principle of Relativity", *Eight lectures on theoretical physics*, New York: Columbia University Press
- Poincaré, Henri (1889), *Théorie mathématique de la lumière* **1**, Paris: G. Carré & C. Naud Preface partly reprinted in "Science and Hypothesis", Ch. 12.
- Poincaré, Henri (1895), "A propos de la Théorie de M. Larmor" [188], *L'Èclairage électrique* **5**: 5–14. Reprinted in Poincaré, Oeuvres, tome IX, pp. 395–413
- Poincaré, Henri (1898/1913), "The Measure of Time", *The Foundations of Science (The Value of Science)*, New York: Science Press, pp. 222–234

- Poincaré, Henri (1900a), "Les relations entre la physique expérimentale et la physique mathématique" [189], *Revue générale des sciences pures et appliquées* **11**: 1163–1175. Reprinted in "Science and Hypothesis", Ch. 9–10.
- Poincaré, Henri (1900b), "La théorie de Lorentz et le principe de réaction", *Archives néerlandaises des sciences exactes et naturelles* **5**: 252–278. See also the English translation [190].
- Poincaré, Henri (1901a), "Sur les principes de la mécanique", *Bibliothèque du Congrès international de philosophie*: 457–494. Reprinted in "Science and Hypothesis", Ch. 6–7.
- Poincaré, Henri (1901b), *Électricité et optique* [191] *at the Internet Archive*, Paris: Gauthier-Villars
- Poincaré, Henri (1902), *Science and Hypothesis*, London and Newcastle-on-Cyne (1905): The Walter Scott publishing Co.
- Poincaré, Henri (1904/6), "The Principles of Mathematical Physics", *Congress of arts and science, universal exposition, St. Louis, 1904* **1**, Boston and New York: Houghton, Mifflin and Company, pp. 604–622
- Poincaré, Henri (1905b), "On the Dynamics of the Electron", *Comptes Rendus* **140**: 1504–1508. (Wikisource translation)
- Poincaré, Henri (1906), "On the Dynamics of the Electron", *Rendiconti del Circolo matematico di Palermo* **21**: 129–176, doi:10.1007/BF03013466 [192] (Wikisource translation)
- Poincaré, Henri (1908/13), "The New Mechanics", *The foundations of science (Science and Method)*, New York: Science Press, pp. 486–522
- Poincaré, Henri (1909), "La Mécanique nouvelle (Lille)", *Revue scientifique* (Paris) **47**: 170–177
- Poincaré, Henri (1909/10), "The New Mechanics (Göttingen)", *Sechs Vorträge über ausgewählte Gegenstände aus der reinen Mathematik und mathematischen Physik*, Leipzig und Berlin: B.G.Teubner, pp. 41–47
- Poincaré, Henri (1910/1), *Die neue Mechanik (Berlin)*, Leipzig & Berlin: B.G. Teubner
- Poincaré, Henri (1912), "L'hypothèse des quanta", *Revue scientifique* **17**: 225–232 Reprinted in Poincaré 1913, Ch. 6.
- Poincaré, Henri (1913), *Last Essays* [193] *at the Internet Archive*, New York: Dover Publication (1963)
- Ritz, Walter (1908), "Recherches critiques sur l'Électrodynamique Générale" [194], *Annales de Chimie et de Physique* **13**: 145–275, see English translation [195].
- Robb, Alfred A. (1911), *Optical Geometry of Motion: A New View of the Theory of Relativity* [196] *at the Internet Archive*, Cambridge: W. Heffer
- Sagnac, Georges (1913), "The demonstration of the luminiferous aether by an interferometer in uniform rotation", *Comptes Rendus* **157**: 708–710
- Sagnac, Georges (1913), "On the proof of the reality of the luminiferous aether by the experiment with a rotating interferometer", *Comptes Rendus* **157**: 1410–1413
- Searle, George Frederick Charles (1897), "On the Steady Motion of an Electrified Ellipsoid", *Philosophical Magazine*, 5 **44** (269): 329–341
- Sommerfeld, Arnold (1910), "On the Theory of Relativity I: Four-dimensional Vector Algebra", *Annalen der Physik* **337** (9): 749–776, Bibcode:1910AnP...337..749S [197], doi:10.1002/andp.19103370904 [198]
- Sommerfeld, Arnold (1910), "On the Theory of Relativity II: Four-dimensional Vector Analysis", *Annalen der Physik* **338** (14): 649–689, Bibcode:1910AnP...338..649S [199], doi:10.1002/andp.19103381402 [200]
- Stokes, George Gabriel (1845), "On the Aberration of Light", *Philosophical Magazine* **27**: 9–15
- Streintz, Heinrich (1883), *Die physikalischen Grundlagen der Mechanik* [201] *at the Internet Archive*, Leipzig: B.G. Teubner
- Thomson, Joseph John (1881), "On the Electric and Magnetic Effects produced by the Motion of Electrified Bodies", *Philosophical Magazine*, 5 **11** (68): 229–249

- Tolman, Richard Chase (1912), "The mass of a moving body", *Philosophical Magazine* **23**: 375–380
- Varičak, Vladimir (1911), "On Ehrenfest's Paradox", *Physikalische Zeitschrift* **12**: 169
- Varičak, Vladimir (1912), "On the Non-Euclidean Interpretation of the Theory of Relativity", *Jahresbericht der Deutschen Mathematiker-Vereinigung* **21**: 103–127
- Voigt, Woldemar (1887), "On the Principle of Doppler", *Nachrichten von der Königl. Gesellschaft der Wissenschaften und der Georg-Augusts-Universität zu Göttingen* (2): 41–51
- Wien, Wilhelm (1900), "On the Possibility of an Electromagnetic Foundation of Mechanics", *Annalen der Physik* **310** (7): 501–513, Bibcode:1901AnP...310..501W [202], doi:10.1002/andp.19013100703 [203]
- Wien, Wilhelm (1904a), "Über die Differentialgleichungen der Elektrodynamik für bewegte Körper. I", *Annalen der Physik* **318** (4): 641–662, Bibcode:1904AnP...318..641W [204], doi:10.1002/andp.18943180402 [205]
- Wien, Wilhelm (1904a), "Über die Differentialgleichungen der Elektrodynamik für bewegte Körper. II", *Annalen der Physik* **318** (4): 663–668, Bibcode:1904AnP...318..663W [206], doi:10.1002/andp.18943180403 [207]
- Wien, Wilhelm (1904b), "Erwiderung auf die Kritik des Hrn. M. Abraham", *Annalen der Physik* **319** (8): 635–637, Bibcode:1904AnP...319..635W [208], doi:10.1002/andp.19043190817 [209]

Notes and Secondary sources

[1] Whittaker (1951), 128ff
[2] Whittaker (1951), 240ff
[3] Whittaker (1951), 319ff
[4] Janssen/Stachel (2004), 20
[5] Whittaker (1951), 107ff
[6] Whittaker (1951), 386f
[7] Janssen/Stachel (2004), 4–15
[8] Whittaker (1951), 390f
[9] Whittaker (1951), 386ff
[10] Janssen/Stachel (2004), 18–19
[11] Janssen/Stachel (2004), 19–20
[12] Miller (1981), 114–115
[13] Pais (1982), Chap. 6b
[14] Miller (1981), 99–100
[15] Brown (2001)
[16] Miller (1981), 27–29
[17] Janssen (1995), Chap. 3.3
[18] Janssen (1995), Ch. 3.3
[19] Miller (1982)
[20] Zahar (1989)
[21] Galison (2002)
[22] Janssen (1995), Ch. 3.1
[23] Macrossan (1986)
[24] Janssen/Stachel (2004), 31–32
[25] Miller (1981), 46
[26] Whittaker (1951), 306ff; (1953) 51f
[27] Janssen (1995), Ch. 3.4
[28] Miller (1981), 46, 103
[29] Darrigol (2005), 18–21
[30] Miller (1981), 47–54
[31] Miller (1981), 61–67
[32] Miller (1981), 359–360
[33] Lange (1886)
[34] Giulini (2001), Ch. 4
[35] DiSalle (2002)
[36] Goenner (2008)
[37] Archibald (1914)

[38] Boyce Gibson (1928)
[39] Hentschel (1990), 153f.
[40] Galison (2003)
[41] Katzir (2005), 272–275
[42] Darrigol (2005), 10–11
[43] Galison (2002), Ch. 4 – Etherial Time
[44] Darrigol (2000), 369–372
[45] Janssen (1995), Ch. 3.3, 3.4
[46] Miller (1981), Chap. 1, Footnote 57
[47] Miller (1981), 75ff
[48] Katzir (2005), 275–277
[49] Miller (1981), 79–86
[50] Katzir (2005), 280–288
[51] Walter (2007), Ch. 1
[52] Miller (1981), 216–217
[53] Whittaker (1953), 27–77
[54] Zahar (1989), 149–200
[55] Logunov (2004)
[57] Holton (1973/1988), 196–206
[58] Miller (1981)
[59] Pais (1982), 126–128
[60] Hentschel (1990), 3–13
[61] Darrigol (2005), 15–18
[62] Katzir (2005), 286–288
[63] Whittaker (1951)
[64] For many other experiments on light constancy and relativity, see PhysicsFaq: What is the experimental basis of special relativity? (http://math.ucr.edu/home/baez/physics/Relativity/SR/experiments.html)
[65] Holton (1988)
[66] Janssen (1995), Ch. 4
[67] Rynasiewicz/Renn (2006)
[68] Stachel (1982)
[69] Darrigol (2004), 624
[70] Miller (1981), 86–92
[71] Born (1956), 193
[72] Miller (1981), 334–352
[73] Miller (1981), 88
[74] Pauli (1921), 636–637
[75] Miller (1981), 329–330
[76] Pauli (1921), 634–636
[77] Miller (1981), 359–367
[78] Laue (1921), pp. 25 & 146–148
[79] Laue (1921), pp. 25–26 & 204–206
[80] Bjerknes (2002)
[81] Walter (1999a), 49
[82] Klein (1910)
[83] Miller (1981), Ch. 7.4.6
[84] Walter (1999b), Ch. 3
[85] Miller (1981), Ch. 12.5.8
[86] Janssen/Mecklenburg (2007)
[87] Pauli (1921), 555–556
[88] Miller (1981), 218–219
[89] Walter (1999b)
[90] Miller (1981), 245–253
[91] Miller (1981), 257–264
[92] Pais (2000), pp. 177-183
[93] Pauli (1921), 626-628
[94] Warwick (2003)
[95] Pauli (1921), 704
[96] Rindler (2001)

[97] Pauli (1921), 690–691

[98] Pauli (1921), 556–557

[99] Pais (1982), 11a

[100] Miller (1981), Ch. 7.4.12

[101] Norton (2005)

[102] Walter (2007)

[103] A century of relativity, Irwin I. Shapiro, Reviews of Modern Physics, 1999, (http://zandra.phys.yorku.ca/menary/courses/phys2040/misc/relativity.pdf)

[104] http://adsabs.harvard.edu/abs/1902AnP...315..105A

[105] http://dx.doi.org/10.1002%2Fandp.19023150105

[106] http://libcoll.mpiwg-berlin.mpg.de/elib/all_documents/Abrah_Neuer_01_1915

[107] http://adsabs.harvard.edu/abs/1964PhL....12..260A

[108] http://dx.doi.org/10.1016%2F0031-9163%2864%2991095-9

[109] http://fisicavolta.unipv.it/percorsi/pdf/press.pdf

[110] http://dx.doi.org/10.1112%2Fplms%2Fs2-8.1.223

[111] http://gallica.bnf.fr/ark:/12148/bpt6k3109m/f215.chemindefer

[112] http://gallica.bnf.fr/ark:/12148/bpt6k31103/f703.table

[113] http://adsabs.harvard.edu/abs/1909AnP...335....1B

[114] http://dx.doi.org/10.1002%2Fandp.19093351102

[115] http://adsabs.harvard.edu/abs/1977PhRvL..39.1051B

[116] http://dx.doi.org/10.1103%2FPhysRevLett.39.1051

[117] http://adsabs.harvard.edu/abs/1903AnP...316..270B

[118] http://dx.doi.org/10.1002%2Fandp.19033160604

[119] http://adsabs.harvard.edu/abs/1910Sci....31..767C

[120] http://dx.doi.org/10.1126%2Fscience.31.803.767

[121] http://www.ncbi.nlm.nih.gov/pubmed/17758464

[122] http://dx.doi.org/10.1112%2Fplms%2Fs2-8.1.77

[123] http://www.fourmilab.ch/etexts/einstein/specrel/

[124] http://www.fourmilab.ch/etexts/einstein/E_mc2/www/

[125] http://adsabs.harvard.edu/abs/1906AnP...325..627E

[126] http://dx.doi.org/10.1002%2Fandp.19063250814

[127] http://adsabs.harvard.edu/abs/1907AnP...328..371E

[128] http://dx.doi.org/10.1002%2Fandp.19073280713

[129] http://adsabs.harvard.edu/abs/1908JRE.....4..411E

[130] http://www.physik.uni-augsburg.de/annalen/history/einstein-papers/1908_26_532-540.pdf

[131] http://adsabs.harvard.edu/abs/1908AnP...331..532E

[132] http://dx.doi.org/10.1002%2Fandp.19083310806

[133] http://www.physik.uni-augsburg.de/annalen/history/einstein-papers/1912_38_1059-1064.pdf

[134] http://adsabs.harvard.edu/abs/1912AnP...343.1059E

[135] http://dx.doi.org/10.1002%2Fandp.19123431014

[136] http://adsabs.harvard.edu/abs/1889Sci....13..390F

[137] http://dx.doi.org/10.1126%2Fscience.ns-13.328.390

[138] http://www.ncbi.nlm.nih.gov/pubmed/17819387

[139] http://gallica.bnf.fr/ark:/12148/bpt6k15337j/f845.table

[140] http://adsabs.harvard.edu/abs/1911AnP...339..825F

[141] http://dx.doi.org/10.1002%2Fandp.19113390502

[142] http://gallica.bnf.fr/ark:/12148/bpt6k883998

[143] http://adsabs.harvard.edu/abs/1904AnP...320..344H

[144] http://dx.doi.org/10.1002%2Fandp.19043201206

[145] http://adsabs.harvard.edu/abs/1905AnP...321..589H

[146] http://dx.doi.org/10.1002%2Fandp.19053210312

[147] http://adsabs.harvard.edu/abs/1890AnP...276..577H

[148] http://dx.doi.org/10.1002%2Fandp.18902760803

[149] http://adsabs.harvard.edu/abs/1890AnP...277..369H

[150] http://dx.doi.org/10.1002%2Fandp.18902771102

[151] http://adsabs.harvard.edu/abs/1906AnP...324..487K

[152] http://dx.doi.org/10.1002%2Fandp.19063240303

[153] http://vlp.mpiwg-berlin.mpg.de/references?id=lit4135

[154] http://amshistorica.unibo.it/diglib.php?inv=7&int_ptnum=108&term_ptnum=302

[155] http://adsabs.harvard.edu/abs/1897RSPTA.190..205L
[156] http://dx.doi.org/10.1098%2Frsta.1897.0020
[157] http://adsabs.harvard.edu/abs/1907AnP...328..738L
[158] http://dx.doi.org/10.1002%2Fandp.19073280910
[159] http://adsabs.harvard.edu/abs/1907AnP...328..989L
[160] http://dx.doi.org/10.1002%2Fandp.19073281015
[161] http://www.archive.org/details/dasrelativittsp00lauegoog
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[167] http://www.archive.org/details/electronstheory00lorerich
[168] http://dx.doi.org/10.1007%2FBF02392073
[169] http://adsabs.harvard.edu/abs/1928ApJ....68..341M
[170] http://dx.doi.org/10.1086%2F143148
[171] http://www.jwdt.com/~paysan/mach.pdf
[172] http://adsabs.harvard.edu/abs/1865RSPT..155..459C
[173] http://dx.doi.org/10.1098%2Frstl.1865.0008
[174] http://www.archive.org/details/electricandmag02maxwrich
[175] http://adsabs.harvard.edu/abs/1925ApJ....61..140M
[176] http://dx.doi.org/10.1086%2F142879
[177] http://adsabs.harvard.edu/abs/1915AnP...352..927M
[178] http://dx.doi.org/10.1002%2Fandp.19153521505
[179] http://adsabs.harvard.edu/abs/1907AnP...327..867V
[180] http://dx.doi.org/10.1002%2Fandp.19073270504
[181] http://www.archive.org/details/ueberdieprincip00neumgoog
[182] http://gallica.bnf.fr/ark:/12148/bpt6k153486/f542.table
[183] http://adsabs.harvard.edu/abs/1914AnP...350..529N
[184] http://dx.doi.org/10.1002%2Fandp.19143502005
[185] http://gallica.bnf.fr/ark:/12148/bpt6k153455.image.f545
[186] http://adsabs.harvard.edu/abs/1913AnP...347..533N
[187] http://dx.doi.org/10.1002%2Fandp.19133471303
[188] http://www.new.dli.ernet.in/scripts/FullindexDefault.htm?path1=/data/upload/0050/246&first=412&last=724&barcode=1990050050241
[189] http://gallica.bnf.fr/ark:/12148/bpt6k17075r/f1167.table
[190] http://www.physicsinsights.org/poincare-1900.pdf
[191] http://www.archive.org/details/electriciteetopt019479mbp
[192] http://dx.doi.org/10.1007%2FBF03013466
[193] http://www.archive.org/details/mathematicsandsc001861mbp
[194] http://gallica.bnf.fr/ark:/12148/bpt6k349439/f143.table
[195] http://www.datasync.com/~rsf1/crit/1908a.htm
[196] http://www.archive.org/details/opticalgeometryo00robbrich
[197] http://adsabs.harvard.edu/abs/1910AnP...337..749S
[198] http://dx.doi.org/10.1002%2Fandp.19103370904
[199] http://adsabs.harvard.edu/abs/1910AnP...338..649S
[200] http://dx.doi.org/10.1002%2Fandp.19103381402
[201] http://www.archive.org/details/diephysikalisch00stregoog
[202] http://adsabs.harvard.edu/abs/1901AnP...310..501W
[203] http://dx.doi.org/10.1002%2Fandp.19013100703
[204] http://adsabs.harvard.edu/abs/1904AnP...318..641W
[205] http://dx.doi.org/10.1002%2Fandp.18943180402
[206] http://adsabs.harvard.edu/abs/1904AnP...318..663W
[207] http://dx.doi.org/10.1002%2Fandp.18943180403
[208] http://adsabs.harvard.edu/abs/1904AnP...319..635W
[209] http://dx.doi.org/10.1002%2Fandp.19043190817

- Archibald, R.C. (1914), "Time as a fourth dimension" (http://projecteuclid.org/euclid.bams/1183422749), *Bull. Amer. Math. Soc.* **20** (8): 409–412, doi: 10.1090/S0002-9904-1914-02511-X (http://dx.doi.org/10.1090/

S0002-9904-1914-02511-X)

- Born, Max (1964), *Einstein's Theory of Relativity*, Dover Publications, ISBN 0-486-60769-0
- Born, Max (1956), *Physics in my generation* (http://www.archive.org/details/physucsinmygener006567mbp), London & New York: Pergamon Press, pp. 189–206
- Brown, Harvey R. (2001), "The origins of length contraction: I. The FitzGerald-Lorentz deformation hypothesis" (http://philsci-archive.pitt.edu/archive/00000218/), *American Journal of Physics* **69** (10): 1044–1054, arXiv: gr-qc/0104032 (http://arxiv.org/abs/gr-qc/0104032), Bibcode: 2001AmJPh..69.1044B (http://adsabs.harvard.edu/abs/2001AmJPh..69.1044B), doi: 10.1119/1.1379733 (http://dx.doi.org/10.1119/1.1379733)
- Darrigol, Olivier (2000), *Electrodynamics from Ampére to Einstein*, Oxford: Clarendon Press, ISBN 0-19-850594-9
- Darrigol, Olivier (2004), "The Mystery of the Einstein-Poincaré Connection", *Isis* **95** (4): 614–626, doi: 10.1086/430652 (http://dx.doi.org/10.1086/430652), PMID 16011297 (http://www.ncbi.nlm.nih.gov/pubmed/16011297)
- Darrigol, Olivier (2005), "The Genesis of the theory of relativity" (http://www.bourbaphy.fr/darrigol2.pdf), *Séminaire Poincaré* **1**: 1–22
- Robert DiSalle (Summer 2002), "Space and Time: Inertial Frames" (http://plato.stanford.edu/archives/sum2002/entries/spacetime-iframes/), in Edward N. Zalta, *The Stanford Encyclopedia of Philosophy*
- Einstein, Albert (1989), "The Swiss Years: Writings, 1900–1909", in Stachel, John et al., *The Collected Papers of Albert Einstein* **2**, Princeton: Princeton University Press, ISBN 0-691-08526-9
- Galison, Peter (2003), *Einstein's Clocks, Poincaré's Maps: Empires of Time*, New York: W.W. Norton, ISBN 0-393-32604-7
- Giulini, Domenico (2001), "Das Problem der Trägheit" (http://www.mpiwg-berlin.mpg.de/Preprints/P190.PDF), *Preprint, Max-Planck Institut für Wissenschaftsgeschichte* **190**: 11–12, 25–26
- Goenner, Hubert (2008), "On the history of geometrization of space-time", *414. Heraeus-Seminar*, arXiv: 0811.4529 (http://arxiv.org/abs/0811.4529), Bibcode: 2008arXiv0811.4529G (http://adsabs.harvard.edu/abs/2008arXiv0811.4529G).
- Hentschel, Klaus (1990), *Interpretationen und Fehlinterpretationen der speziellen und der allgemeinen Relativitätstheorie durch Zeitgenossen Albert Einsteins*, Basel – Boston – Bonn: Birkhäuser, ISBN 3-7643-2438-4
- Holton, Gerald (1988), *Thematic Origins of Scientific Thought: Kepler to Einstein*, Harvard University Press, ISBN 0-674-87747-0
- Janssen, Michel (1995), *A Comparison between Lorentz's Ether Theory and Special Relativity in the Light of the Experiments of Trouton and Noble, (thesis)* (http://www.mpiwg-berlin.mpg.de/litserv/diss/janssen_diss/)
- Janssen, Michel & Mecklenburg, Matthew (2007), "From classical to relativistic mechanics: Electromagnetic models of the electron" (http://philsci-archive.pitt.edu/archive/00001990/), in V. F. Hendricks, et al., *Interactions: Mathematics, Physics and Philosophy*, Dordrecht: Springer, pp. 65–134
- Janssen, Michel & Stachel, John (2008), *The Optics and Electrodynamics of Moving Bodies* (http://www.mpiwg-berlin.mpg.de/Preprints/P265.PDF)
- Katzir, Shaul (2005), "Poincaré's Relativistic Physics: Its Origins and Nature", *Phys. Perspect.* **7** (3): 268–292, Bibcode: 2005PhP.....7..268K (http://adsabs.harvard.edu/abs/2005PhP.....7..268K), doi: 10.1007/s00016-004-0234-y (http://dx.doi.org/10.1007/s00016-004-0234-y)
- Keswani, G. H., Kilmister, C. W. (1983), "Intimations Of Relativity: Relativity Before Einstein" (http://osiris.sunderland.ac.uk/webedit/allweb/news/Philosophy_of_Science/PIRT2002/Intimations of Relativity.doc), *Brit. J. Phil. Sci.* **34** (4): 343–354, doi: 10.1093/bjps/34.4.343 (http://dx.doi.org/10.1093/bjps/34.4.343)

Wikipedia:Link rot

- Klein, Felix (1910/21), "Über die geometrischen Grundlagen der Lorentzgruppe", *Gesammelte mathematische Abhandlungen* **1**: 533–552
- Lange, Ludwig (1886), *Die geschichtliche Entwicklung des Bewegungsbegriffes* (http://www.archive.org/details/diegeschichtlic00langgoog), Leipzig: Wilhelm Engelmann
- Laue, Max von (1921), *Die Relativitätstheorie*, Braunschweig: Friedr. Vieweg & Sohn. = 4. Edition of Laue (1911).
- Macrossan, M. N. (1986), "A Note on Relativity Before Einstein" (http://espace.library.uq.edu.au/view.php?pid=UQ:9560), *Brit. J. Phil. Sci.* **37**: 232–234
- Alberto A. Martínez (2009), *Kinematics: the lost origins of Einstein's relativity*, Johns Hopkins University Press, ISBN 0-8018-9135-3
- Miller, Arthur I. (1981), *Albert Einstein's special theory of relativity. Emergence (1905) and early interpretation (1905–1911)*, Reading: Addison–Wesley, ISBN 0-201-04679-2
- Norton, John D. (2004), "Einstein's Investigations of Galilean Covariant Electrodynamics prior to 1905" (http://philsci-archive.pitt.edu/archive/00001743/), *Archive for History of Exact Sciences* **59** (1): 45–105, Bibcode: 2004AHES...59...45N (http://adsabs.harvard.edu/abs/2004AHES...59...45N), doi: 10.1007/s00407-004-0085-6 (http://dx.doi.org/10.1007/s00407-004-0085-6)
- Norton, John D. (2005), "Einstein, Nordström and the early demise of scalar, lorentz covariant theories of gravitation" (http://www.pitt.edu/~jdnorton/papers/Nordstroem.pdf), in Renn, Jürgen, *The Genesis of General Relativity (Vol. 1)*, Printed in the Netherlands: Kluwer
- Pais, Abraham (1982), *Subtle is the Lord: The Science and the Life of Albert Einstein*, New York: Oxford University Press, ISBN 0-19-520438-7
- Pauli, Wolfgang (1921), "Die Relativitätstheorie" (http://gdz.sub.uni-goettingen.de/no_cache/dms/load/img/?IDDOC=201990), *Encyclopädie der mathematischen Wissenschaften* **5** (2): 539–776
- Polanyi, Michael (1974), *Personal Knowledge: Towards a Post-Critical Philosophy*, Chicago: University Press, ISBN 0-226-67288-3
- Rindler, Wolfgang (2001), *Relativity: Special, General, and Cosmological*, Oxford University Press, ISBN 0-19-850836-0
- Rynasiewicz, Robert; Renn, Jürgen. (2006), "The turning point for Einstein's annus mirabilis." (http://philsci-archive.pitt.edu/archive/00002567/), *Studies in History and Philosophy of Modern Physics* **31** (1): 5–35
- Schaffner, Kenneth F. (1972), *Nineteenth-century aether theories*, Oxford: Pergamon Press, pp. 99–117 und 255–273, ISBN 0-08-015674-6
- Stachel, John (1982), "Einstein and Michelson: the Context of Discovery and Context of Justification", *Astronomische Nachrichten* **303** (1): 47–53, Bibcode: 1982AN....303...47S (http://adsabs.harvard.edu/abs/1982AN....303...47S), doi: 10.1002/asna.2103030110 (http://dx.doi.org/10.1002/asna.2103030110)
- Stachel, John (2002), *Einstein from "B" to "Z"*, Boston: Birkhäuser, ISBN 0-8176-4143-2
- Staley, Richard (2009), *Einstein's generation. The origins of the relativity revolution*, Chicago: University of Chicago Press, ISBN 0-226-77057-5
- Walter, Scott (1999a), "Minkowski, mathematicians, and the mathematical theory of relativity" (http://www.univ-nancy2.fr/DepPhilo/walter/papers/mmm.xml), in H. Goenner, J. Renn, J. Ritter, and T. Sauer, *Einstein Studies* **7**, Birkhäuser, pp. 45–86
- Walter, Scott (1999b), "The non-Euclidean style of Minkowskian relativity" (http://www.univ-nancy2.fr/DepPhilo/walter/papers/nes.xml), in J. Gray, *The Symbolic Universe: Geometry and Physics*, Oxford

University Press, pp. 91–127

- Walter, Scott (2005), "Henri Poincaré and the theory of relativity" (http://www.univ-nancy2.fr/DepPhilo/walter/papers/hpeinstein2005.htm), in Renn, J., *Albert Einstein, Chief Engineer of the Universe: 100 Authors for Einstein* **3**, Berlin: Wiley-VCH, pp. 162–165
- Walter, Scott (2007), "Breaking in the 4-vectors: the four-dimensional movement in gravitation, 1905–1910" (http://www.univ-nancy2.fr/DepPhilo/walter/papers/breaking2007.pdf), in Renn, J., *The Genesis of General Relativity* **3**, Berlin: Springer, pp. 193–252
- Warwick, Andrew (2003), *Masters of Theory: Cambridge and the Rise of Mathematical Physics*, Chicago: University of Chicago Press, ISBN 0-226-87375-7
- Whittaker, Edmund Taylor (1910), *A History of the theories of aether and electricity* (http://www.archive.org/details/historyoftheorie00whitrich) (1. ed.), Dublin: Longman, Green and Co.
- Whittaker, Edmund Taylor (1951), *A History of the theories of aether and electricity Vol. 1: The classical theories* (2. ed.), London: Nelson
- Whittaker, Edmund Taylor (1953), "The relativity theory of Poincaré and Lorentz", *A History of the theories of aether and electricity; Vol. 2: The modern theories 1900–1926*, London: Nelson, pp. 27–77
- Zahar, Elie (1989), *Einstein's Revolution: A Study in Heuristic*, Chicago: Open Court Publishing Company, ISBN 0-8126-9067-2

Non mainstream

- Bjerknes, Christopher Jon (2002), "A Short History of the Concept of Relative Simultaneity in the Special Theory of Relativity" (http://itis.volta.alessandria.it/episteme/ep6/ep6-bjerk3.htm), *Episteme* **6**
- Logunov, A.A. (2004), *Henri Poincaré and relativity theory*, Moscow: Nauka, arXiv: physics/0408077 (http://arxiv.org/abs/physics/0408077), Bibcode: 2004physics...8077L (http://adsabs.harvard.edu/abs/2004physics...8077L), ISBN 5-02-033964-4

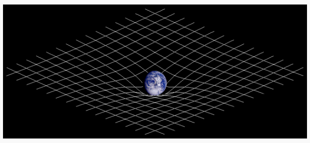
External links

- O'Connor, John J.; Robertson, Edmund F., "Special relativity" (http://www-history.mcs.st-andrews.ac.uk/HistTopics/Special_relativity.html), *MacTutor History of Mathematics archive*, University of St Andrews.
- Mathpages: Corresponding States (http://www.mathpages.com/rr/s1-05/1-05.htm), The End of My Latin (http://www.mathpages.com/rr/s3-06/3-06.htm), Who Invented Relativity? (http://www.mathpages.com/rr/s8-08/8-08.htm), Poincaré Contemplates Copernicus (http://www.mathpages.com/home/kmath305/kmath305.htm)

Light and general relativity

History of general relativity

General relativity



$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Introduction
Mathematical formulation
Resources · Tests

General relativity (GR) is a theory of gravitation that was developed by Albert Einstein between 1907 and 1915, with contributions by many others after 1915. According to general relativity, the observed gravitational attraction between masses results from the warping of space and time by those masses.

Before the advent of general relativity, Newton's law of universal gravitation had been accepted for more than two hundred years as a valid description of the gravitational force between masses, even though Newton himself did not regard the theory as the final word on the nature of gravity. Within a century of Newton's formulation, careful astronomical observation revealed unexplainable variations between the theory and the observations. Under Newton's model, gravity was the result of an attractive force between massive objects. Although even Newton was bothered by the unknown nature of that force, the basic framework was extremely successful at describing motion.

However, experiments and observations show that Einstein's description accounts for several effects that are unexplained by Newton's law, such as minute anomalies in the orbits of Mercury and other planets. General relativity also predicts novel effects of gravity, such as gravitational waves, gravitational lensing and an effect of gravity on time known as gravitational time dilation. Many of these predictions have been confirmed by experiment, while others are the subject of ongoing research. For example, although there is indirect evidence for gravitational waves, direct evidence of their existence is still being sought by several teams of scientists in experiments such as the LIGO and GEO 600 projects.

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. Their strong gravity is thought to be responsible for the intense radiation emitted by certain types of astronomical objects (such as active galactic nuclei or microquasars). General relativity is also part of the framework of the standard Big Bang model of cosmology.

Creation of general relativity

Early investigations

As Einstein later said, the reason for the development of general relativity was the preference of inertial motion within special relativity, while a theory which from the outset prefers no state of motion (even accelerated ones) appeared more satisfactory to him.[1] So, while still working at the patent office in 1907, Einstein had what he would call his "happiest thought". He realized that the principle of relativity could be extended to gravitational fields.

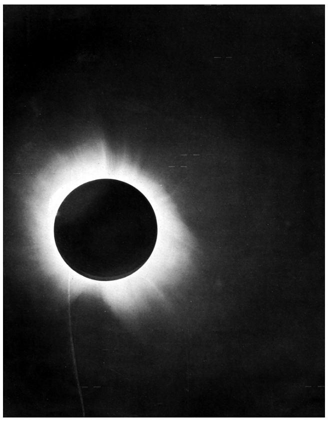
Consequently, in 1907 (published 1908) he wrote an article on acceleration under special relativity.[2] In that article, he argued that free fall is really inertial motion, and that for a freefalling observer the rules of special relativity must apply. This argument is called the Equivalence principle. In the same article, Einstein also predicted the phenomenon of gravitational time dilation.

In 1911, Einstein published another article expanding on the 1907 article.[3] There, he thought about the case of a uniformly accelerated box not in a gravitational field, and noted that it would be indistinguishable from a box sitting still in an unchanging gravitational field. He used special relativity to see that the rate of clocks at the top of a box accelerating upward would be faster than the rate of clocks at the bottom. He concludes that the rates of clocks depend on their position in a gravitational field, and that the difference in rate is proportional to the gravitational potential to first approximation.

Also the deflection of light by massive bodies was predicted. Although the approximation was crude, it allowed him to calculate that the deflection is nonzero. German astronomer Erwin Finlay-Freundlich publicized Einstein's challenge to scientists around the world.[4] This urged astronomers to detect the deflection of light during a solar eclipse, and gave Einstein confidence that the scalar theory of gravity proposed by Gunnar Nordström was incorrect. But the actual value for the deflection that he calculated was too small by a factor of two, because the approximation he used doesn't work well for things moving at near the speed of light. When Einstein finished the full theory of general relativity, he would rectify this error and predict the correct amount of light deflection by the sun.

Another of Einstein's notable thought experiments about the nature of the gravitational field is that of the rotating disk (a variant of the Ehrenfest paradox). He imagined an observer making experiments on a rotating turntable. He noted that such an observer would find a different value for the mathematical constant π than the one predicted by Euclidean geometry. The reason is that the radius of a circle would be measured with an uncontracted ruler, but, according to special relativity, the circumference would seem to be longer because the ruler would be contracted. Since Einstein believed that the laws of physics were local, described by local fields, he concluded from this that spacetime could be locally curved. This led him to study Riemannian geometry, and to formulate general relativity in this language.

Developing general relativity



Eddington's photograph of a solar eclipse, which confirmed Einstein's theory that light "bends".

In 1912, Einstein returned to Switzerland to accept a professorship at his *alma mater*, the ETH. Once back in Zurich, he immediately visited his old ETH classmate Marcel Grossmann, now a professor of mathematics, who introduced him to Riemannian geometry and, more generally, to differential geometry. On the recommendation of Italian mathematician Tullio Levi-Civita, Einstein began exploring the usefulness of general covariance (essentially the use of tensors) for his gravitational theory. For a while Einstein thought that there were problems with the approach, but he later returned to it and, by late 1915, had published his general theory of relativity in the form in which it is used today.[5] This theory explains gravitation as distortion of the structure of spacetime by matter, affecting the inertial motion of other matter. During World War I, the work of Central Powers scientists was available only to Central Powers academics, for national security reasons. Some of Einstein's work did reach the United Kingdom and the United States through the efforts of the Austrian Paul Ehrenfest and physicists in the Netherlands, especially 1902 Nobel Prize-winner Hendrik Lorentz and Willem de Sitter of Leiden University. After the war ended, Einstein maintained his relationship with Leiden University, accepting a contract as an *Extraordinary Professor*; for ten years, from 1920 to 1930, he travelled to Holland regularly to lecture.[6]

In 1917, several astronomers accepted Einstein 's 1911 challenge from Prague. The Mount Wilson Observatory in California, U.S., published a solar spectroscopic analysis that showed no gravitational redshift.[7] In 1918, the Lick Observatory, also in California, announced that it too had disproved Einstein's prediction, although its findings were not published.[8]

However, in May 1919, a team led by the British astronomer Arthur Stanley Eddington claimed to have confirmed Einstein's prediction of gravitational deflection of starlight by the Sun while photographing a solar eclipse with dual expeditions in Sobral, northern Brazil, and Príncipe, a west African island.[4] Nobel laureate Max Born praised general relativity as the "greatest feat of human thinking about nature";[9] fellow laureate Paul Dirac was quoted saying it was "probably the greatest scientific discovery ever made".[10] The international media guaranteed Einstein's global renown.

There have been claims that scrutiny of the specific photographs taken on the Eddington expedition showed the experimental uncertainty to be comparable to the same magnitude as the effect Eddington claimed to have demonstrated, and that a 1962 British expedition concluded that the method was inherently unreliable.[] The deflection of light during a solar eclipse was confirmed by later, more accurate observations.[11] Some resented the newcomer's fame, notably among some German physicists, who later started the *Deutsche Physik* (German Physics) movement.[][12]

General covariance and the hole argument

By 1912, Einstein was actively seeking a theory in which gravitation was explained as a geometric phenomenon. At the urging of Tullio Levi-Civita, Einstein began by exploring the use of general covariance (which is essentially the use of curvature tensors) to create a gravitational theory. However, in 1913 Einstein abandoned that approach, arguing that it is inconsistent based on the "hole argument". In 1914 and much of 1915, Einstein was trying to create field equations based on another approach. When that approach was proven to be inconsistent, Einstein revisited the concept of general covariance and discovered that the hole argument was flawed.

The development of the Einstein field equations

When Einstein realized that general covariance was actually tenable, he quickly completed the development of the field equations that are named after him. However, he made a now-famous mistake. The field equations he published in October 1915 were

$$R_{\mu\nu} = T_{\mu\nu},$$

where $R_{\mu\nu}$ is the Ricci tensor, and $T_{\mu\nu}$ the energy-momentum tensor. This predicted the non-Newtonian perihelion precession of Mercury, and so had Einstein very excited. However, it was soon realized that they were inconsistent with the local conservation of energy-momentum unless the universe had a constant density of mass-energy-momentum. In other words, air, rock and even a vacuum should all have the same density. This inconsistency with observation sent Einstein back to the drawing board. However, the solution was all but obvious, and in November 1915 Einstein published the actual Einstein field equations:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = T_{\mu\nu},$$

where R is the Ricci scalar and $g_{\mu\nu}$ the metric tensor. With the publication of the field equations, the issue became one of solving them for various cases and interpreting the solutions. This and experimental verification have dominated general relativity research ever since.

Einstein and Hilbert

Although Einstein is credited with finding the field equations, the German mathematician David Hilbert published them in an article before Einstein's article. This has resulted in accusations of plagiarism against Einstein (never from Hilbert), and assertions that the field equations should be called the "Einstein-Hilbert field equations". However, Hilbert did not press his claim for priority and someWikipedia:Avoid weasel words have asserted that Einstein submitted the correct equations before Hilbert amended his own work to include them. This suggests that Einstein developed the correct field equations first, though Hilbert may have reached them later independently (or even learned of them afterwards through his correspondence with Einstein).[13] However, others have criticized those assertions.[14]

Sir Arthur Eddington

In the early years after Einstein's theory was published, Sir Arthur Eddington lent his considerable prestige in the British scientific establishment in an effort to champion the work of this German scientist. Because the theory was so complex and abstruse (even today it is popularly considered the pinnacle of scientific thinking; in the early years it was even more so), it was rumored that only three people in the world understood it. There was an illuminating, though probably apocryphal, anecdote about this. As related by Ludwik Silberstein,[15] during one of Eddington's lectures he asked "Professor Eddington, you must be one of three persons in the world who understands general relativity." Eddington paused, unable to answer. Silberstein continued "Don't be modest, Eddington!" Finally, Eddington replied "On the contrary, I'm trying to think who the third person is."

Solutions

The Schwarzschild solution

Since the field equations are non-linear, Einstein assumed that they were unsolvable. However, in 1916 Karl Schwarzschild discovered an exact solution for the case of a spherically symmetric spacetime surrounding a massive object in spherical coordinates. This is now known as the Schwarzschild solution. Since then, many other exact solutions have been found.

The expanding universe and the cosmological constant

In 1922, Alexander Friedmann found a solution in which the universe may expand or contract, and later Georges Lemaître derived a solution for an expanding universe. However, Einstein believed that the universe was apparently static, and since a static cosmology was not supported by the general relativistic field equations, he added a cosmological constant Λ to the field equations, which became

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = T_{\mu\nu}.$$

This permitted the creation of steady-state solutions, but they were unstable: the slightest perturbation of a static state would result in the universe expanding or contracting. In 1929, Edwin Hubble found evidence for the idea that the universe is expanding. This resulted in Einstein dropping the cosmological constant, referring to it as "the biggest blunder in my career". At the time, it was an ad hoc hypothesis to add in the cosmological constant, as it was only intended to justify one result (a static universe).

More exact solutions

Progress in solving the field equations and understanding the solutions has been ongoing. The solution for a spherically symmetric charged object was discovered by Reissner and later rediscovered by Nordström, and is called the Reissner-Nordström solution. The black hole aspect of the Schwarzschild solution was very controversial, and Einstein did not believe that singularities could be real. However, in 1957 (two years after Einstein's death in 1955), Martin Kruskal published a proof that black holes are called for by the Schwarzschild Solution. Additionally, the solution for a rotating massive object was obtained by Kerr in the 1960s and is called the Kerr solution. The Kerr-Newman solution for a rotating, charged massive object was published a few years later.

Testing the theory

The perihelion precession of Mercury was the first evidence that general relativity is correct. Sir Arthur Stanley Eddington's 1919 expedition in which he confirmed Einstein's prediction for the deflection of light by the Sun during the total solar eclipse of 29 May 1919 helped to cement the status of general relativity as a likely true theory. Since then many observations have confirmed the correctness of general relativity. These include studies of binary pulsars, observations of radio signals passing the limb of the Sun, and even the GPS system.

Alternative theories

There have been various attempts to find modifications to general relativity. The most famous of these are the Brans-Dicke theory (also known as scalar-tensor theory), and Rosen's bimetric theory. Both of these theories proposed changes to the field equations of general relativity, and both suffer from these changes permitting the presence of bipolar gravitational radiation. As a result, Rosen's original theory has been refuted by observations of binary pulsars. As for Brans-Dicke (which has a tunable parameter ω such that ω = ▯ is the same as general relativity), the amount by which it can differ from general relativity has been severely constrained by these observations.

In addition, general relativity is inconsistent with quantum mechanics, the physical theory that describes the wave-particle duality of matter, and quantum mechanics does not currently describe gravitational attraction at relevant (microscopic) scales. There is a great deal of speculation in the physics community as to the modifications that might be needed to both general relativity and quantum mechanics in order to unite them consistently. The speculative theory that unites general relativity and quantum mechanics is usually called quantum gravity, prominent examples of which include String Theory and Loop Quantum Gravity.

More about GR history

Kip Thorne identifies the "golden age of general relativity" as the period roughly from 1960 to 1975 during which the study of general relativity,[16] which had previously been regarded as something of a curiosity, entered the mainstream of theoretical physics. During this period, many of the concepts and terms which continue to inspire the imagination of gravitation researchers (and members of the general public) were introduced, including black holes and 'gravitational singularity'. At the same time, in closely related development, the study of physical cosmology entered the mainstream and the Big Bang became well established.

The study of general relativity, entered the mainstream of theoretical physics. Terms were introduced, including black holes and 'gravitational singularity'. At the same time, the study of physical cosmology entered the mainstream including the Big Bang.

- Role of curvature in general relativity;
- Theoretical importance of the black holes;
- Importance of geometrical machinery and levels of mathematical structure, especially local versus global spacetime structure;
- Overall legitimacy of cosmology by the wider physics community.

A competitor to general relativity (the Brans-Dicke theory), and the first "precision tests" of gravitation theories. Discoveries in observational astronomy are:

- Quasars (objects the size of the solar system and as luminous as a hundred modern galaxies, so distant that they date from the early years of the universe);
- Pulsars (soon interpreted as spinning neutron stars);
- The first credible candidate black hole, Cygnus X-1;
- The cosmic background radiation, hard evidence of the Big Bang and the subsequent expansion of the universe.

Notes

[1] Albert Einstein, Nobel lecture (http://nobelprize.org/nobel_prizes/physics/laureates/1921/einstein-lecture.html) in 1921

[2] page 454 (Wir betrachen zwei Bewegung systeme ...)

[3] (also in *Collected Papers* Vol. 3, document 23)

[4] Crelinsten, Jeffrey. " Einstein's Jury: The Race to Test Relativity (http://www.pupress.princeton.edu/titles/8165.html)". *Princeton University Press.* 2006. Retrieved on 13 March 2007. ISBN 978-0-691-12310-3

[10] Jürgen Schmidhuber. " Albert Einstein (1879–1955) and the 'Greatest Scientific Discovery Ever' (http://www.idsia.ch/~juergen/einstein.html)". 2006. Retrieved on 4 October 2006.

[11] See the table in MathPages Bending Light (http://www.mathpages.com/rr/s6-03/6-03.htm)

[12] For a discussion of astronomers' attitudes and debates about relativity, see , especially chapters 6, 9, 10 and 11.

[13] Leo Corry, Jürgen Renn, John Stachel: "Belated Decision in the Hilbert-Einstein Priority Dispute", SCIENCE, Vol. 278, 14 November 1997 - article text (http://www.tau.ac.il/~corry/publications/articles/science.html)

[14] Friedwart Winterberg's response to the Cory-Renn-Stachel paper (http://physics.unr.edu/faculty/winterberg/Hilbert-Einstein.pdf) as printed in "Zeitschrift für Naturforschung" 59a (http://www.znaturforsch.com/c59a.htm), 715-719.

[15] John Waller (2002), *Einstein's Luck*, Oxford University Press, ISBN 0-19-860719-9

[16] , Extract of page 74 (http://books.google.com/books?id=yLy4b61rfPwC&pg=PA74)

References

- Pais, Abraham (1982). *Subtle is the lord: the science and life of Albert Einstein*. Oxford: Oxford University Press. ISBN 0-19-853907-X.
- Einstein, A.; Grossmann, M. (1913). "Entwurf einer verallgemeinerten Relativitätstheorie und einer Theorie der Gravitation" [Outline of a Generalized Theory of Relativity and of a Theory of Gravitation]. *Zeitschrift für Mathematik und Physik* **62**: 225–261.
- *Einstein and the Changing Worldviews of Physics* (editors—Lehner C., Renn J., Schemmel M.) 2012 (Birkhäuser).
- Genesis of general relativity series (http://www.bun.kyoto-u.ac.jp/~suchii/gen.GR.html)

Relativity priority dispute

Albert Einstein presented the theories of Special Relativity and General Relativity in groundbreaking publications that either contained no formal references to previous literature, or referred only to a small number of his predecessors for fundamental results on which he based his theories, most notably to the work of Hendrik Lorentz for special relativity, and to the work of Gauss, Riemann, and Mach for general relativity. Subsequently claims have been put forward about both theories, asserting that they were formulated, either wholly or in part, by others before Einstein. At issue is the extent to which Einstein and various other individuals should be credited for the formulation of these theories, based on priority considerations.

The general history of the development of these theories, including the contributions made by many other scientists, is found at History of special relativity and History of general relativity.

The candidates for credit

Concerning special relativity, the most important names that are mentioned in discussions about the distribution of credit are Albert Einstein, Hendrik Lorentz, Henri Poincaré, and Hermann Minkowski. Consideration is also given to numerous other scientists for either anticipations of some aspects of the theory, or else for contributions to the development or elaboration of the theory. These include Woldemar Voigt, August Föppl, Joseph Larmor, Emil Cohn, Friedrich Hasenöhrl, Max Planck, Max von Laue, Gilbert Newton Lewis and Richard Chase Tolman, etc. In addition, polemics exist about alleged contributions of others such as Olinto De Pretto, and Einstein's first wife Mileva Marić, although these are not considered to have any foundation by serious scholars.[1]

Concerning general relativity, there is a controversy about the amount of credit that should go to Einstein, Grossmann, and David Hilbert. Many others (such as Gauss, Riemann, William Kingdon Clifford, Ricci, and Levi-Civita) contributed to the development of the mathematical tools and geometrical ideas underlying the theory. Also polemics exist about alleged contributions of others such as Paul Gerber.

Undisputed and well known facts

The following facts are undisputed and generally known:

Special relativity

- In 1889, ([Poi89]), Henri Poincaré argued that the ether might be unobservable, in which case the existence of the ether is a metaphysical question, and he suggested that some day the ether concept would be thrown aside as useless. However, in the same book (Ch. 10) he considered the ether a "convenient hypothesis" and continued to use the concept also in later papers in 1908 ([Poi08], Book 3) and 1912 ([Poi13], Ch. 6).

- In 1895, Poincaré argued that experiments like that of Michelson-Morley show that it seems to be impossible to detect the absolute motion of matter or the relative motion of matter in relation to the ether. In [Poi00] he called this the Principle of Relative Motion, i.e., that the laws of movement should be the same in all inertial frames. Alternative terms used by Poincaré were "relativity of space" and "principle of relativity".[2] In 1904 he expanded that principle by saying: *"The principle of relativity, according to which the laws of physical phenomena must be the same for a stationary observer as for one carried along in a uniform motion of translation, so that we have no means, and can have none, of determining whether or not we are being carried along in such a motion."* However, he also stated that we do not know if this principle will turn out to be true, but that it is interesting to determine what the principle implies.
- In [Poi00], Poincaré published a paper in which he said that radiation could be considered as a fictitious fluid with an equivalent mass of $m_r = E/c^2$. He derived this interpretation from Lorentz's 'theory of electrons' which incorporated Maxwell's radiation pressure.
- Poincaré had described a synchronization procedure for clocks at rest relative to each other in [Poi00] and again in [Poi04]. So two events, which are simultaneous in one frame of reference, are not simultaneous in another frame. It is very similar to the one later proposed by Einstein.[3] However, Poincaré distinguished between "local" or "apparent" time of moving clocks, and the "true" time of resting clocks in the ether. In [Poi02] he argued that "some day, no doubt, the ether will be thrown aside as useless".
- Lorentz' paper [Lor04] containing the transformations bearing his name appeared in 1904.
- Albert Einstein in [Ein05c] derived the Lorentz equations by using the principle of constancy of velocity of light and the relativity principle. He was the first to argue that those principles (along with certain other basic assumptions about the homogeneity and isotropy of space, usually taken for granted by theorists) are sufficient to derive the theory. See Postulates of special relativity. He said: "*The introduction of a* luminiferous ether *will prove to be superfluous inasmuch as the view here to be developed will not require an* absolutely stationary space *provided with special properties, nor assign a velocity-vector to a point of the empty space in which electromagnetic processes take place.*" * Einstein's *Elektrodynamik* paper [Ein05c] contains no formal references to other literature. It does mention, in §9, part II, that the results of the paper are in agreement with Lorentz's electrodynamics. Poincaré is not mentioned in this paper, although he is cited formally in a paper on special relativity written by Einstein the following year.
- In 1905 Einstein was the first to suggest that when a material body lost energy (either radiation or heat) of amount ΔE , its mass decreased by the amount $\Delta E/c^2$.[4]
- Hermann Minkowski showed in 1907 that the theory of special relativity could be elegantly described using a four-dimensional spacetime, which combines the dimension of time with the three dimensions of space.
- Einstein in 1920 returned to a concept of aether having no state of motion.[5][6]

General relativity

- The proposal to describe gravity by means of a pseudo-Riemannian metric was first made by Einstein and Grossmann in the so-called *Entwurf* theory published 1913 [*citation needed*]. This was followed by several attempts of Einstein to find valid field equations for this theory of gravity.
- David Hilbert invited Einstein to Göttingen for a week to give six 2-hour lectures on general relativity, which he did in June–July 1915. Einstein stayed at Hilbert's house during this visit. Hilbert started working on a combined theory of gravity and electromagnetism, and Einstein and Hilbert exchanged correspondence until November 1915. Einstein gave four lectures on his theory on Nov 4, Nov 11, Nov 18 and Nov 25 in Berlin, published as [Ein15a], [Ein15b], [Ein15c], [Ein15d].
- November 4, Einstein published non-covariant field equations and on November 11 returned to the field equations of the "Entwurf" papers, which he now made covariant by the assumption that the trace of the energy-momentum tensor was zero, as it was for electromagnetism.
- Einstein sent Hilbert proofs of his papers of Nov 4 and Nov 11. (Sauer 99, notes 63, 66)

- Nov 15 Invitation issued for Nov 20 meeting at the Academy in Göttingen. "Hilber legt vor in die Nachrichten: Grundgleichungen der Physik". (Sauer 99, note 73)
- Nov 16 Hilbert spoke at the Göttingen Mathematical Society "Grundgleichungen der Physik" (Sauer 99, note 68). Talk not published.
- Nov 16 or Nov 17 Hilbert sent Einstein some information about his talk of Nov 16 (letter lost)
- Nov 18 Einstein replies to Hilbert's letter (received by Hilbert Nov 19) saying as far as he (Einstein) could tell Hilbert's system was equivalent to the one he (Einstein) had found in the preceding weeks. (Sauer 99, note 72). Einstein also told Hilbert in this letter that he (Einstein) had "considered the only possible generally covariant field equations three years earlier", adding that "The difficulty was not to find generally covariant equations for the $g^{\mu\nu}$;this is easy with the help of the Riemann tensor. What was difficult instead was to recognize that these equations form a generalization, and that is, a simple and natural generalization of Newton's law" (A. Einstein to D. Hilbert, 18 Nov, Einstein Archives Call No. 13-093). Einstein also told Hilbert in that letter that he (Einstein) had calculated the correct perihelion advance for Mercury, using covariant field equations based on the assumption that the trace of the energy momentum tensor vanished as it did for electromagnetism.
- Nov 18 Einstein presents the calculation of the perihelion advance to Prussian Academy.
- Nov 20 Hilbert lectured to the Göttingen Academy. The proofs of his paper show that Hilbert proposed a non-covariant set of equations as the fundamental equations of physics. Thus he wrote "in order to keep the deterministic characteristic of the fundamental equations of physics [...] four further non-covariant equations ... [are] unavoidable." (proofs, pages 3 and 4. quoted by Corry et al.). Hilbert then derives these four extra equations and continues "these four differential equations [...] supplement the gravitational equations [...] to yield a system of 14 equations for the 14 potentials $g^{\mu\nu}$: q_s the system of fundamental equations of physics". (proofs, page 7, quoted by Corry et al.).
- In his last lecture on Nov 25 Einstein submitted the correct field equations. The published paper (Einstein 1915d) appeared on December 2, and it did not mention Hilbert.
- Hilbert's paper took considerably longer to appear. He had galley proofs that were marked "December 6" by the printer in December 1915. Most of the galley proofs have been preserved, but about a quarter of a page is missing.[7] The extant part of the proofs contains Hilbert's action from which the field equations can be obtained by taking a variational derivative, and using the contracted Bianchi identity derived in theorem III of Hilbert's paper, though this was not done in the extant proofs.
- Hilbert rewrote his paper for publication (in Mar 1916), changing the treatment of the energy theorem, dropping a non-covariant gauge condition on the coordinates to produce a covariant theory, and adding a new credit to Einstein for introducing the gravitational potentials $g_{\mu\nu}$ into the theory of gravity. In the final paper he said his differential equations seemed to agree with the "magnificent theory of general relativity established by Einstein in his later papers"[8]
- The events of late November through December 1915 caused bad feelings from Einstein towards Hilbert. In a November 25 letter to Zangger, Einstein accused Hilbert (without mentioning his name) of attempts to appropriate ('nostrify') his theory. On Dec 4, Hilbert nominated Einstein for election as a corresponding member of the Göttingen Mathematical Society. In a December 20 letter to Hilbert, Einstein proposed to settle the dispute.
- The 1916 paper was rewritten and republished in 1924 [Hil24], where Hilbert wrote: *Einstein [...] kehrt schließlich in seinen letzten Publikationen geradewegs zu den Gleichungen meiner Theorie zurück.* (*Einstein [...] in his most recent publications, returns directly to the equations of my theory.*)[9]

Disputed claims

The following things seem to be unclear, unknown or disputed:

Special relativity

- To what degree Einstein was familiar with Poincaré's work
    - It is known that Einstein was familiar with [Poi02], but it is not known to what extent he was familiar with other work of Poincaré in 1905. However it is known that he knew [Poi00] in 1906, because he quoted it in [Ein06].
- Lorentz' paper [Lor04] containing the transformations bearing his name appeared in 1904. The question is whether Einstein was familiar in 1905 with either this paper itself or a review of it (which appeared in the Annalen der Physik).
- To what degree Einstein was following other physicists' work at the time. Some authors claim that Einstein worked in relative isolation and with restricted access to the physics literature in 1905. Others, however, disagree; a personal friend of Einstein, Maurice Solovine, later acknowledged that he and Einstein both pored *for weeks* over Poincaré's 1902 book, keeping them "breathless for weeks on end" [Rot06].
- Whether his wife, Mileva Marić, may have contributed to Einstein's work, although this question is not considered to have any foundation by serious scholars.[1]

General relativity

- Before 1997, "the commonly accepted view was that David Hilbert completed the general theory of relativity at least 5 days before Albert Einstein submitted his conclusive paper on this theory on 25 November 1915. Hilbert's article, bearing the date of submission 20 November 1915 but published only on 31 March 1916, presents a generally covariant theory of gravitation, including field equations essentially equivalent to those in Einstein's paper" (Corry, Renn and Stachel, 1997). Since the discovery of printer's proofs of Hilbert's paper of Nov 20, dated 6 Dec 1915, which show a number of differences from the finally published paper, this 'commonly accepted view' has been challenged.[*citation needed*]
- Whether Einstein got the correct mathematical formulation for general relativity from Hilbert, or formulated it independently. Points at issue:
    - The content of Hilbert's November 16 letter/postcard to Einstein is not known. It is however, clear from Einstein's response that it was an account of Hilbert's work.
    - It is not known what was on the missing part of Hilbert's printer proofs. The missing portion is large enough to have contained the field equations in an explicit form. There are several competing speculations about the content of the missing piece.
    - Based on the above, it is not known whether Hilbert had formulated the field equations in an explicit form before December 6 (the date of the printer's proofs) or not.
    - It is known from the proofs that Hilbert introduced four non-covariant equations in order to specify the gravitational potentials g and that this approach was dropped from his revised paper.
- Whether Hilbert ever tried to claim priority for the field equations - it seems clear that he regarded the theory of general relativity as Einstein's theory.
- What Hilbert thought he was referring to when he used the term "equations of my theory" about Einstein's research. Hilbert made a similar remark in a letter to Karl Schwarzschild.[10]

There are a large number of opinions related to these involving questions of "who should get the credit" - these are not enumerated here.

Special Relativity

Historians of special relativity

In his *History of the theories of ether and electricity* from 1953, E. T. Whittaker claimed that relativity is the creation of Lorentz and Poincaré and attributed to Einstein's papers only little importance.[11] However, most historians of science, like Gerald Holton, Arthur I. Miller, Abraham Pais, John Stachel, or Olivier Darrigol have other points of view. They admit that Lorentz and Poincaré developed the mathematics of special relativity, and many scientists originally spoke about the "Lorentz-Einstein theory". But they argue that it was Einstein who completely eliminated the classical ether *and* demonstrated the relativity of space and time. They also argue that Poincaré demonstrated the relativity of space and time only in his *philosophical* writings, but in his *physical* papers he maintained the ether as a privileged frame of reference that is perfectly undetectable, and continued (like Lorentz) to distinguish between "real" lengths and times measured by observers at rest within the aether, and "apparent" lengths and times measured by observers in motion within the aether.[][][][][] Darrigol summarizes:

> *Most of the components of Einstein's paper appeared in others' anterior works on the electrodynamics of moving bodies. Poincaré and Alfred Bucherer had the relativity principle. Lorentz and Larmor had most of the Lorentz transformations, Poincaré had them all. Cohn and Bucherer rejected the ether. Poincaré, Cohn, and Abraham had a physical interpretation of Lorentz's local time. Larmor and Cohn alluded to the dilation of time. Lorentz and Poincaré had the relativistic dynamics of the electron. None of these authors, however, dared to reform the concepts of space and time. None of them imagined a new kinematics based on two postulates. None of them derived the Lorentz transformations on this basis. None of them fully understood the physical implications of these transformations. It all was Einstein's unique feat.*[]

Comments by Lorentz, Poincaré, and Einstein

Lorentz

In a paper that was written in 1914 and published in 1921,[12] Lorentz appreciated Poincaré's Palermo paper (1906)[13] of Poincaré on relativity. Lorentz stated:

> “I did not indicate the transformation which suits best. That was done by Poincaré and then by Mr. Einstein and Minkowski. [..] Because I had not thought of the direct way which led there, and because I had the idea that there is an essential difference between systems x, y, z, t and x',y',z',t'. In one we use - such was my thought - coordinate axes which have a fixed position in the aether and which we can call "true" time; in the other system, on the contrary, we would deal with simple auxiliary quantities whose introduction is only a mathematical artifice. [..] I did not establish the principle of relativity as rigorously and universally true. Poincaré, on the contrary, obtained a perfect invariance of the equations of electrodynamics, and he formulated the "postulate of relativity", terms which he was the first to employ. [..] Let us add that by correcting the imperfections of my work he never reproached me for them. ”

However, a 1916 reprint of his main work "The theory of electrons" contains notes (written in 1909 and 1915) in which Lorentz sketched the differences between his results and that of Einstein as follows:[14]

> “[p. 230]: the chief difference [is] that Einstein simply postulates what we have deduced, with some difficulty and not altogether satisfactorily, from the fundamental equations of the electromagnetic field. [p. 321]: The chief cause of my failure was my clinging to the idea that the variable t only can be considered as the true time and that my local time t' must be regarded as no more than an auxiliary mathematical quantity. In Einstein's theory, on the contrary, t' plays the same part as t; if we want to describe phenomena in terms of x', y', z', t' we must work with these variables exactly as we could do with x, y, z, t. ”

Regarding the fact, that in this book Lorentz only mentioned Einstein and not Poincaré in connection with a) the synchronisation by light signals, b) the reciprocity of the Lorentz transformation, and c) the relativistic transformation law for charge density, Janssen comments:[15]

> [p.90]: My guess is that it has to do with the fact that Einstein made the physical interpretation of the Lorentz transformation the basis for a remarkably clear and simple discussion of the electrodynamics of moving bodies, whereas Poincaré's remarks on the physical interpretation of Lorentz transformed quantities may have struck Lorentz as inconsequential philosophical asides in expositions that otherwise closely followed his own. I also have a sense that Lorentz found Einstein's physically very intuitive approach more appealing than Poincaré's rather abstract but mathematically more elegant approach.

And at a conference on the Michelson-Morley experiment in 1927 at which Lorentz and Michelson were present, Michelson suggested that Lorentz was the initiator of the theory of relativity. Lorentz then replied:[16]

> I considered my time transformation only as a heuristic working hypothesis. So the theory of relativity is really solely Einstein's work. And there can be no doubt that he would have conceived it even if the work of all his predecessors in the theory of this field had not been done at all. His work is in this respect independent of the previous theories.

Poincaré

Poincaré attributed the development of the new mechanics almost entirely to Lorentz. He only mentioned Einstein in connection with the photoelectric effect,[] but not in connection with special relativity. For example, in 1912 Poincaré raises the question whether "the mechanics of Lorentz" will still exist after the development of the quantum theory. He wrote:[]

> In all instances in which it differs from that of Newton, the mechanics of Lorentz endures. We continue to believe that no body in motion will ever be able to exceed the speed of light; that the mass of a body is not a constant, but depends on its speed and the angle formed by this speed with the force which acts upon the body; that no experiment will ever be able to determine whether a body is at rest or in absolute motion either in relation to absolute space or even in relation to the ether.

Einstein

It is now known that Einstein was well aware of the scientific research of his time. The well known historian of science, Jürgen Renn, Director of the Max Planck Institute for the History of Science wrote on Einstein's contributions to the Annalen der Physik:[17]

> The Annalen also served as a source of modest additional income for Einstein, who wrote more than twenty reports for its Beiblätter - mainly on the theory of heat - thus demonstrating an impressive mastery of the contemporary literature. This activity started in 1905.[18] and probably resulted from his earlier publications in the Annalen in this field. Going by his publications between 1900 and early 1905, one would conclude that Einstein's specialty was thermodynamics.

Einstein wrote in 1907[19] that one needed only to realize that an auxiliary quantity that was introduced by Lorentz and that he called "local time" can simply be defined as "time." In 1909[20] and 1912[21] Einstein explained:[22]

> ...it is impossible to base a theory of the transformation laws of space and time on the principle of relativity alone. As we know, this is connected with the relativity of the concepts of "simultaneity" and "shape of moving bodies." To fill this gap, I introduced the principle of the constancy of the velocity of light, which I borrowed from H. A. Lorentz's theory of the stationary luminiferous ether, and which, like the principle of relativity, contains a physical assumption that seemed to be justified only by the relevant experiments (experiments by Fizeau, Rowland, etc.)[21]
>
> —Albert Einstein (1912), translated by Anna Beck (1996).

But he recognized that this principle together with the principle of relativity makes the ether useless and leads to special relativity. It is also known[23] that he read Poincaré's 1902-book "Science and hypothesis" before 1905, which included:

- philosophical assessments on the relativity of space, time, and simultaneity
- the definition of the principle of relativity and the opinion that a violation of that principle can never be detected
- the possible non-existence of the ether

- many remarks on the non-Euclidean geometry.

Einstein refers to Poincaré in connection with the inertia of energy in 1906[24] and the non-Euclidean geometry in 1921,[25] but not in connection with the Lorentz transformation, the relativity principle or the synchronisation procedure by light signals. However, in the last years before Einstein's death he acknowledged some of Poincaré's contributions (according to Darrigol, maybe because his biographer Pais in 1950 sent him a copy of Poincarè's Palermo paper, which he said that he had not read before). Einstein wrote in 1953:[]

> “There is no doubt, that the special theory of relativity, if we regard its development in retrospect, was ripe for discovery in 1905. Lorentz had already recognized that the transformations named after him are essential for the analysis of Maxwell’s equations, and Poincaré deepened this insight still further. Concerning myself, I knew only Lorentz's important work of 1895 [...] but not Lorentz's later work, nor the consecutive investigations by Poincaré. In this sense my work of 1905 was independent. [..] The new feature of it was the realization of the fact that the bearing of the Lorentz transformation transcended its connection with Maxwell's equations and was concerned with the nature of space and time in general. A further new result was that the "Lorentz invariance" is a general condition for any physical theory. ”

General Relativity

Did Hilbert claim priority for parts of General Relativity?

Kip Thorne concludes, based on Hilbert's 1924 paper, that Hilbert regarded the General Theory of relativity as Einstein's: "Quite naturally, and in accord with Hilbert's view of things, the resulting law of warpage was quickly given the name the Einstein field equation rather than being named after Hilbert. Hilbert had carried out the last few mathematical steps to its discovery independently and almost simultaneously with Einstein, but Einstein was responsible for essentially everything that preceded those steps...".[26] However, Kip Thorne also stated, "Remarkably, Einstein was not the first to discover the correct form of the law of warpage [. . . .] Recognition for the first discovery must go to Hilbert."[26]

Arguments have been made that Hilbert claimed priority for the field equations themselves; the sources cited for this are:

- Hilbert's article (dated 20 November 1915), when it appeared in 1916, contained the text "Die so zu Stande kommenden Differentialgleichungen der Gravitation sind, wie mir scheint, mit der von Einstein in seinen späteren Abhandlungen aufgestellten großzügigen Theorie der allgemeinen Relativität in gutem Einklang." - in translation, "The differential equations of gravity arrived at in this way are, I think, in good agreement with those of Einstein in his later papers in which he presented his comprehensive theory of general relativity." Hilbert refers here to the "later papers" of Einstein, obviously to distinguish them from the Entwurf theory of 1913 and the preliminary papers prior to the end of November 1915 when Einstein published the equations of general relativity in their final form. Hilbert's sentence has sometimes been mis-interpreted[*citation needed*] by replacing the word "later" with "subsequent", and suggesting that Hilbert was writing in a clairvoyant sense about papers of Einstein that would be written subsequent to the paper that Hilbert was presently writing. Serious scholarsWikipedia:Avoid weasel words dismiss such misconstruals as obvious nonsense.
- Wuensch [10] points out that Hilbert refers to the field equations of gravity as "meine Theorie" ("my theory") in his February 6, 1916 letter to Schwarzschild. This, however, is not at issue, since no one disputes that Hilbert had his own "theory", which Einstein criticized as naive and overly ambitious. Hilbert's theory was based on the work of Mie combined with Einstein's principle of general covariance, but applied to matter and electromagnetism as well as gravity.
- Mehra [27] and Bjerknes[28] point out that Hilbert's 1924 version of the article contained the sentence "... und andererseits auch Einstein, obwohl wiederholt von abweichenden und unter sich verschiedenen Ansätzen ausgehend, kehrt schließlich in seinen letzten Publikationen geradenwegs zu den Gleichungen meiner Theorie zurück" - "Einstein [...] in his last publications ultimately returns directly to the equations of my theory.".[29] These statements of course do not have any particular bearing on the matter at issue. No one disputes that Hilbert

has "his" theory, which was a very ambitious attempt to combine gravity with a theory of matter and electromagnetism along the lines of Mie's theory, and that his equations for gravitation agreed with those that Einstein presented beginning in his Nov 25 paper (which Hilbert refers to as Einstein's later papers to distinguish them from previous theories of Einstein). None of this bears on the precise origin of the trace term in the Einstein field equations (a feature of the equations that, while theoretically significant, does not have any effect on the vacuum equations, from which all the empirical tests proposed by Einstein were derived).

- Sauer says "the independence of Einstein's discovery was never a point of dispute between Einstein and Hilbert ... Hilbert claimed priority for the introduction of the Riemann scalar into the action principle and the derivation of the field equations from it, "[30] (Sauer mentions a letter and a draft letter where Hilbert defends his priority for the action functional) "and Einstein admitted publicly that Hilbert (and Lorentz) had succeeded in giving the equations of general relativity a particularly lucid form by deriving them from a single variational principle"[*citation needed*]. Sauer also stated, "And in a draft of a letter to Weyl, dated 22 April 1918, written after he had read the proofs of the first edition of Weyl's 'Raum-Zeit-Materie' Hilbert also objected to being slighted in Weyl's exposition. In this letter again 'in particular the use of the Riemannian curvature [scalar] in the Hamiltonian integral' ('insbesondere die Verwendung der Riemannschen Krümmung unter dem Hamiltonschen Integral') was claimed as one of his original contributions. SUB Cod. Ms. Hilbert 457/17."[30]
- Einstein wrote to Hilbert on 20 December 1915 that there was an "ill-feeling between us" and it has been suspected that this ill feeling was the result of Einstein's bitterness over Hilbert's "nostrification" of his (Einstein's) theory. Others have suggested that Hilbert might have felt that Einstein had derived some benefit or hints from his (Hilbert's) letters, and that those had helped him to arrive at the trace term of the field equations, and if so, that Einstein should have acknowledged this in his paper. But this is pure speculation, aside from Einstein's comment that he believed others (presumably Hilbert) had tried to "nostrify" his theory.

So far, there seems to be no consensus that these statements form a clear claim by Hilbert to have published the field equations first.

Did Einstein develop the field equations independently?

For a long time, it was believed that Einstein and Hilbert found the field equations of gravity independently. While Hilbert's paper was submitted somewhat earlier than Einstein's, it only appeared in 1916, after Einstein's field equations paper had appeared in print. For this reason there was no good reason to suspect plagiarism on either side. In 1978, a November 18, 1915 letter from Einstein to Hilbert[*citation needed*] resurfaced, in which Einstein thanked Hilbert for sending an explanation of Hilbert's work. This was not unexpected to most scholars, who were well aware of the correspondence between Hilbert and Einstein that November, and who continued to hold the view expressed by Albrecht Fölsing in his Einstein biography:

> In November, when Einstein was totally absorbed in his theory of gravitation, he essentially only corresponded with Hilbert, sending Hilbert his publications and, on November 18, thanking him for a draft of his article. Einstein must have received that article immediately before writing this letter. Could Einstein, casting his eye over Hilbert's paper, have discovered the term which was still lacking in his own equations, and thus 'nostrified' Hilbert? [31]

In the very next sentence, after asking the rhetorical question, Folsing answers it with "This is not really probable...", and then goes on to explain in detail why

> "[Einstein's] eventual derivation of the equations was a logical development of his earlier arguments—in which, despite all the mathematics, physical principles invariably predominated. His approach was thus quite different from Hilbert's, and Einstein's achievements can, therefore, surely be regarded as authentic."

In their 1997 *Science* paper,[32] Corry, Renn and Stachel quote the above passage and comment that "the arguments by which Einstein is exculpated are rather weak, turning on his slowness in fully grasping Hilbert's mathematics", and so they attempted to find more definitive evidence of the relationship between the work of Hilbert and Einstein, basing their work largely on a recently discovered pre-print of Hilbert's paper. A discussion of the controversy around this paper is given below.

Those who contend that Einstein's paper was motivated by the information obtained from Hilbert have referred to the following sources:

- The correspondence between Hilbert and Einstein mentioned above. More recently, it became known that Einstein was also given notes of Hilbert's November 16 talk about his theory.[10]
- Einstein's November 18 paper on the perihelion motion of Mercury, which still refers to the incomplete field equations of November 4 and 11. (The perihelion motion depends only on the vacuum equations, which are unaffected by the trace term that was added to complete the field equations.) Reference to the final form of the equations appears only in a footnote added to the paper, indicating that Einstein had not known the final form of the equations on November 18. This is not controversial, and is consistent with the well-known fact that Einstein did not complete the field equations (with the trace term) until November 25.
- Letters of Hilbert, Einstein, and other scientists may be used in attempts to make guesses about the content of Hilbert's letter to Einstein, which is not preserved, or of Hilbert's lecture in Göttingen on November 16.

Those who contend that Einstein's work takes priority over Hilbert's,[32] or that both authors did their work independently[33] have used the following arguments:

- Hilbert modified his paper in December 1915, and the November 18 version sent to Einstein did not contain the final form of the field equations. The extant part of the printer proofs does not have the explicit field equations. This is the point of view defended by Corry, Renn, Stachel, and Sauer.
- Sauer (1999) and Todorov (2005) agree with Corry, Renn and Satchel that Hilbert's proofs show that Hilbert had originally presented a non-covariant theory, which was dropped from the revised paper. Corry *et al.* quote from the proofs: "Since our mathematical theorem ... can provide only ten essentially independent equations for the 14 potentials [...] and further, maintaining general covariance makes quite impossible more than ten essential independent equations [...] then, in order to keep the deterministic characteristic of the fundamental equations of physics [...] four further non-covariant equations ... [are] unavoidable." (proofs, pages 3 and 4. Corry *et al.*) Hilbert derives these four extra equations and continues "these four differential equations [...] supplement the gravitational equations [...] to yield a system of 14 equations for the 14 potentials $g^{\mu\nu}$, q_s: the system of fundamental equations of physics". (proofs, page 7. Corry *et al.*). Hilbert's first theory (lecture Nov 16, lecture Nov 20, proofs Dec 6) was titled "The fundamental equations of Physics". In proposing non-covariant fundamental equations, based on the Ricci tensor but restricted in this way, Hilbert was following the causality requirement that Einstein and Grassman had introduced in the Entwurf papers of 1913.[30]
- One may attempt to reconstruct the way in which Einstein may have arrived at the field equations independently. This is, for instance, done in the paper of Logunov, Mestvirishvili and Petrov quoted below.[34] Renn and Sauer[35] investigate the notebook used by Einstein in 1912 and claim he was close to the correct theory at that time.

Attackers and defenders

This section cites notable publications where people have expressed a view on the issues outlined above.

Special relativity

Sir Edmund Whittaker (1954)

In 1954, Sir Edmund Taylor Whittaker, an English mathematician and historian of science, credited Poincaré with the equation $E = mc^2$, and he included a chapter entitled *The Relativity Theory of Poincaré and Lorentz* in his book *A History of the Theories of Aether and Electricity*.[36] He credited Poincaré and Lorentz, and especially alluded to Lorentz's 1904 paper (dated by Whittaker as 1903), Poincaré's St. Louis speech (The Principles of

Mathematical Physics) of September 1904, and Poincaré's June 1905 paper. Whittaker attributed to Einstein's relativity paper only little importance, i.e., the formulation of the Doppler and aberration formulas.

Gerald Holton (1960)

Whittaker's claims were criticized by Gerald Holton (1960, 1973).[] He argued that there are fundamental differences between the theories of Einstein on one hand, and Poincaré and Lorentz on the other hand. Einstein radically reformulated the concepts of space and time, and by that removed "absolute space" and thus the stationary luminiferous aether from physics. On the other hand, Holton argued that Poincaré and Lorentz still adhered to the stationary aether concept, and tried only to modify Newtonian dynamics, not to replace it. Holton argued, that "Poincaré's silence" (i.e., why Poincaré never mentioned Einstein's contributions to relativity) was due to their fundamental different conceptual viewpoints. Einstein's views on space and time and the abandonment of the aether were, according to Holton, not acceptable to Poincaré, therefore the latter only referred to Lorentz as the creator of the "new mechanics". Holton also pointed out that although Poincaré's 1904 St. Louis speech was "acute and penetrating" and contained a "principle of relativity" that is confirmed by experience and needs new development, it did not "enunciate a new relativity principle". He also alluded to mistakes of Whittaker, like predating Lorentz's 1904 paper (published April 1904) to 1903.

Similar views as Holton's were later (1967, 1970) also expressed by his former student, Stanley Goldberg.[]

G. H. Keswani (1965)

In a 1965 series of articles tracing the history of relativity,[37] Keswani claimed that Poincaré and Lorentz should have the main credit for special relativity - claiming that Poincaré pointedly credited Lorentz multiple times, while Lorentz credited Poincaré and Einstein, refusing to take credit for himself. He also downplayed the theory of general relativity, saying "Einstein's general theory of relativity is only a theory of gravitation and of modifications in the laws of physics in gravitational fields".[37] This would leave the special theory of relativity as the unique theory of relativity. Keswani cited also Vladimir Fock for this same opinion.

This series of articles prompted responses, among others from Herbert Dingle and Karl Popper.

Dingle said, among other things, ".. the 'principle of relativity' had various meanings, and the theories associated with it were quite distinct; they were not different forms of the same theory. Each of the three protagonists.... was very well aware of the others .... but each preferred his own views"[38]

Karl Popper says "Though Einstein appears to have known Poincaré's *Science and Hypothesis* prior to 1905, there is no theory like Einstein's in this great book."[39]

Keswani did not accept the criticism, and replied in two letters also published in the same journal ([40] and [41] - in his reply to Dingle, he argues that the three relativity theories were at heart the same: ".. they meant much that was common. And that much mattered the most."[40]

Dingle commented the year after on the history of crediting: "Until the first World War, Lorentz's and Einstein's theories were regarded as different forms of the same idea, but Lorentz, having priority and being a more established figure speaking a more familiar language, was credited with it." (Dingle 1967, Nature 216 p. 119-122).

Arthur I. Miller (1973)

Miller (1973, 1981)[] agreed with the analysis of Holton and Goldberg, and further argued that although the terminology (like the principle of relativity) used by Poincaré and Einstein were very similar, their content differs sharply. According to Miller, Poincaré used this principle to complete the aether based "electromagnetic world-view" of Lorentz and Abraham. He also argued that Poincaré distinguished (in his July 1905 paper) between "ideal" and "real" systems and electrons. That is, Lorentz's and Poincaré's usage of reference frames lacks an unambiguous physical interpretation, because in many cases they are only mathematical tools, while in Einstein's theory the processes in inertial frames are not only mathematically, but also physically equivalent. Miller wrote in 1981:

> p. 172: "*Although Poincaré's principle of relativity is stated in a manner similar to Einstein's, the difference in content is sharp. The critical difference is that Poincaré's principle admits the existence of the ether, and so considers the velocity of light to be exactly c only when it is measured in coordinate systems at rest in the ether. In inertial reference systems, the velocity of light is c and is independent of the emitter's motion as a result of certain compensatory effects such as the mathematical local time and the hypothesis of an unobservable contraction. Consequently, Poincaré's extension of the relativity principle of relative motion into the dynamics of the electron resided in electromagnetic theory, and not in mechanics...Poincaré came closest to rendering electrodynamics consistent, but not to a relativity theory.*" p. 217: "Poincaré related the imaginary system Σ' to the ether fixed system S'".

Abraham Pais (1982)

In his Einstein biography *Subtle is the Lord* (1982),[] Abraham Pais argued that Poincaré "comes near" to discover special relativity (in his St. Louis lecture of September 1904, and the June 1905 paper), but eventually he failed, because in 1904 and also later in 1909, Poincaré treated length contraction as a third independent hypothesis besides the relativity principle and the constancy of the speed of light. According to Pais, Poincaré thus never understood (or at least he never accepted) special relativity, in which the whole theory including length contraction can simply be derived from two postulates. Consequently, he sharply criticized Whittaker's chapter on the "Relativity theory of Poincaré and Lorentz", saying "*how well the author's lack of physical insight matches his ignorance of the literature*", although Pais admitted that the first book of Whittaker's *History of Aether and Electricity* is a masterpiece.

He also argued that Lorentz never abandoned the stationary aether concept, either before or after 1905:

> p. 118: "*Throughout the paper of 1895, the Fresnel aether is postulated explicitly*"; p. 125: "*Like Voigt before him, Lorentz regarded the transformation ... only as a convenient mathematical tool for proving a physical theorem ... he proposed to call t the general time and t' the local time. Although he didn't say it explicitly, it is evident that to him there was, so to speak, only one true time t.*"; p. 166: "*8.3. Lorentz and the Aether... For example, Lorentz still opines that the contraction of the rods has a dynamic origin. There is no doubt that he had read and understood Einstein's papers by then. However, neither then nor later was he prepared to accept their conclusions as the definitive answer to the problems of the aether.*"

Elie Zahar (1983)

In several papers, Elie Zahar (1983, 2000)[] argued that both Einstein (in his June paper) and Poincaré (in his July paper) independently discovered special relativity. He said that "*though Whittaker was unjust towards Einstein, his positive account of Poincaré's actual achievement contains much more than a simple grain of truth*". According to him, it was Poincaré's unsystematic and sometimes erroneous statements regarding his philosophical papers (often connected with conventionalism), which hindered many to give him due credit. In his opinion, Poincaré was rather a "structural realist" and from that he concludes, that Poincaré actually adhered to the relativity of time and space, while his allusions to the aether are of secondary importance. He continues, that due to his treatment of gravitation and four-dimensional space, Poincaré's 1905/6-paper was superior to Einstein's 1905-paper. Yet Zahar gives also credit to Einstein, who introduced Mass–Energy equivalence, and also transcended special relativity by taking a path leading to the development of general relativity.

John Stachel (1995)

John Stachel (1995)[] argued that there is a debate over the respective contributions of Lorentz, Poincaré and Einstein to relativity. These questions depend on the definition of relativity, and Stachel argued that kinematics and the new view of space and time is the core of special relativity, and dynamical theories must be formulated in accordance with this scheme. Based on this definition, Einstein is the main originator of the modern understanding of special relativity. In his opinion, Lorentz interpreted the Lorentz transformation only as a mathematical device, while

Poincaré's thinking was much nearer to the modern understanding of relativity. Yet Poincaré still believed in the dynamical effects of the aether and distinguished between observers being at rest or in motion with respect to it. Stachel wrote: "*He never organized his many brilliant insights into a coherent theory that resolutely discarded the aether and the absolute time or transcended its electrodynamic origins to derive a new kinematics of space and time on a formulation of the relativity principle that makes no reference to the ether*".

Peter Galison (2002)

In his book *Einstein's clocks, Poincaré's maps* (2002),[][42] Peter Galison compared the approaches of both Poincaré and Einstein to reformulate the concepts of space and time. He wrote: "*Did Einstein really discover relativity? Did Poincaré already have it? These old questions have grown as tedious as they are fruitless.*" This is because it depends on the question, which parts of relativity one considers as essential: the rejection of the aether, the Lorentz transformation, the connection with the nature of space and time, predictions of experimental results, or other parts. For Galison, it is more important to acknowledge that both thinkers were concerned with clock synchronization problems, and thus both developed the new operational meaning of simultaneity. However, while Poincaré followed a constructive approach and still adhered to the concepts of Lorentz's stationary aether and the distinction between "apparent" and "true" times, Einstein abandoned the aether and therefore all times in different inertial frames are equally valid. Galison argued that this does not mean that Poincaré was conservative, since Poincaré often alluded to the revolutionary character of the "new mechanics" of Lorentz.

Christopher Jon Bjerknes (2003)

This author has written several books and articles claiming that Einstein plagiarized the theories of relativity. Examples are "Anticipations of Einstein in the General Theory of Relativity" and "Albert Einstein: the incorrigible plagiarist".[43][28]

Olivier Darrigol (2004)

In his 2004 article, "The Mystery of the Einstein-Poincaré Connection", Darrigol wrote:[]

- "By 1905 Poincaré's and Einstein's reflections on the electrodynamics of moving bodies led them to postulate the universal validity of the relativity principle, according to which the outcome of any conceivable experiment is independent of the inertial frame of reference in which it is performed. In particular, they both assumed that the velocity of light measured in different inertial frames was the same. They further argued that the space and time measured by observers belonging to different inertial systems were related to each other through the Lorentz transformations. They both recognized that the Maxwell-Lorentz equations of electrodynamics were left invariant by these transformations. They both required that every law of physics should be invariant under these transformations. They both gave the relativistic laws of motion. They both recognized that the relativity principle and the energy principle led to paradoxes when conjointly applied to radiation processes. On several points - namely, the relativity principle, the physical interpretation of Lorentz's transformations (to first order), and the radiation paradoxes - Poincaré's relevant publications antedated Einstein's relativity paper of 1905 by at least five years, and his suggestions were radically new when they first appeared. On the remaining points, publication was nearly simultaneous."
- "I turn now to basic conceptual differences. Einstein completely eliminated the ether, required that the expression of the laws of physics should be the same in any inertial frame, and introduced a "new kinematics" in which the space and time measured in different inertial systems were all on exactly the same footing. In contrast, Poincaré maintained the ether as a privileged frame of reference in which "true" space and time were defined, while he regarded the space and time measured in other frames as only "apparent." He treated the Lorentz contraction as a hypothesis regarding the effect of the edgewise motion of a rod through the ether, whereas for Einstein it was a kinematic consequence of the difference between the space and time defined by observers in relative motion. Einstein gave the operational meaning of time dilation, whereas Poincaré never discussed it. Einstein derived the

expression of the Lorentz transformation from his two postulates (the relativity principle and the constancy of the velocity of light in a given inertial system), whereas Poincaré obtained these transformations as those that leave the Maxwell-Lorentz equations invariant. Whereas Einstein, having eliminated the ether, needed a second postulate, in Poincaré's view the constancy of the velocity of light (in the ether frame) derived from the assumption of a stationary ether. Einstein obtained the dynamics of any rapidly moving particle by the direct use of Lorentz covariance, whereas Poincaré reasoned according to a specific model of the electron built up in conformity with Lorentz covariance. Einstein saw that Poincaré's radiation paradoxes could be solved only by assuming the inertia of energy, whereas Poincaré never returned to this question. Lastly, Poincaré immediately proposed a relativistic modification of Newton's law of gravitation and saw the advantages of a four-vector formalism in this context, whereas Einstein waited a couple of years to address this problem complex."

- "These differences between the two theories are sometimes regarded as implying different observable predictions even within the domain of electromagnetism and optics. In reality, there is no such disagreement, for Poincaré's ether is by assumption perfectly undetectable, and every deduction made in Einstein's theory can be translated into a deduction in Poincaré's theory ..."
- In sum, then, Einstein could have borrowed the relativity principle, the definition of simultaneity, the physical interpretation of the Lorentz transformations, and the radiation paradoxes from Poincaré. ... The wisest attitude might be to leave the coincidence of Poincaré's and Einstein's breakthroughs unexplained, ...

Anatoly Alexeevich Logunov on special relativity (2004)

In Anatoly Logunov's book[34] about Poincaré's relativity theory, there is an English translation (on p. 113, using modern notations) of the part of Poincaré's 1900 article containing $E=mc^2$. Logunov states that Poincaré's two 1905 papers are superior to Einstein's 1905 paper. According to Logunov, Poincaré was the first scientist to recognize the importance of invariance under the Poincaré group as a guideline for developing new theories in physics. In chapter 9 of this book, Logunov points out that Poincaré's second paper was the first one to formulate a complete theory of relativistic dynamics, containing the correct relativistic analogue of Newton's $F=ma$.

On p. 142, Logunov points out that Einstein wrote reviews for the *Beiblätter Annalen der Physik,* writing 21 reviews in 1905. In his view, this contradicts the claims that Einstein worked in relative isolation and with limited access to the scientific literature. Among the papers reviewed in the *Beiblätter* in the fourth (of 24) issue of 1905, there is a review of Lorentz' 1904-paper by Richard Gans, which contains the Lorentz transformations. In Logunov's view, this supports the view that Einstein was familiar with the Lorentz' paper containing the correct relativistic transformation in early 1905, while his June 1905 paper does not mention Lorentz in connection with this result.

Harvey R. Brown (2005)

Harvey R. Brown (2005)[44] (who favors a dynamical view of relativistic effects similar to Lorentz, but "*without a hidden aether frame*") wrote about the road to special relativity from Michelson to Einstein in section 4:

> p. 40: "*The cradle of special theory of relativity was the combination of Maxwellian electromagnetism and the electron theory of Lorentz (and to a lesser extent of Larmor) based on Fresnel's notion of the stationary aether....It is well known that Einstein's special relativity was partially motivated by this failure [to find the aether wind], but in order to understand the originality of Einstein's 1905 work it is incumbent on us to review the work of the trailblazers, and in particular Michelson, FitzGerald, Lorentz, Larmor, and Poincaré. After all they were jointly responsible for the discovery of relativistic kinematics, in form if not in content, as well as a significant portion of relativistic dynamics as well.*"

Regarding Lorentz's work before 1905, Brown wrote about the development of Lorentz's "theorem of corresponding states" and then continued:

> p. 54: "*Lorentz's interpretation of these transformations is not the one Einstein would given them and which is standardly embraced today. Indeed, until Lorentz came to terms with Einstein's 1905 work, and somehow*

> *despite Poincaré's warning, he continued to believe that the true coordinate transformations were the Galilean ones, and that the 'Lorentz' transformations ... were merely a useful formal device...*" p. 56. "*Lorentz consistently failed to understand the operational significance of his notions of 'local' time...He did however have an intimation of time dilation in 1899, but inevitably there are caveats...The hypotheses of Lorentz's system were starting to pile up, and the spectre of ad hocness was increasingly hard to ignore.*"

Then the contribution Poincaré's to relativity:

> p. 62: "*Indeed, the claim that this giant of pure and applied mathematics co-discovered special relativity is not uncommon, and it is not hard to see why. Poincaré was the first to extend the relativity principle to optics and electrodynamics exactly. Whereas Lorentz, in his theorem of corresponding states, had from 1899 effectively assumed this extension of the relativity principle up to second-order effects, Poincaré took it to hold for all orders. Poincaré was the first to show that Maxwell's equations with source terms are strictly Lorentz covariant. … Poincaré was the first to use the generalized relativity principle as a constraint on the form of the coordinate transformations. He recognized that the relativity principle implies that the transformations form a group, and in further appealing to spatial isotropy. … Poincaré was the first to see the connection between Lorentz's 'local time', and the issue of clock synchrony. … It is fair to say that Poincaré was the first to understand the relativity of simultaneity, and the conventionality of distant simultaneity. Poincaré anticipated Minkowski's interpretation of the Lorentz transformations as a passive, rigid rotation within a four-dimensional pseudo-Euclidean space-time. He was also aware that the the [*sic*] electromagnetic potentials transform in the manner of what is now called a Minkowski 4-vector. He anticipated the major results of relativistic dynamics (and in particular the relativistic relations between force, momentum and velocity), but not $E=mc^2$ in its full generality.*"

However, Brown continued with the reasons which speak against Poincaré's co-discovery:

> p. 63-64: "*What are the grounds for denying Poincaré the title of co-discoverer of special relativity? ... Although Poincaré understood independently of Einstein how the Lorentz transformations give rise to non-Galilean transformation rules for velocities (indeed Poincaré derived the correct relativistic rules), it is not clear that he had a full appreciation of the modern operational significance attached to coordinate transformations.... he did not seem to understand the role played by the second-order terms in the transformation. Compared with the cases of Lorentz and Larmor, it is even less clear that Poincaré understood either length contraction or time dilation to be a consequence of the coordinate transformation.... What Poincaré was holding out for was no less than a new theory of ether and matter - something far more ambitions than what appeared in Einstein's 1905 relativity paper...p. 65. Like Einstein half a decade later, Poincaré wanted new physics, not a reinterpretations or reorganization of existing notions.*"

Brown denies the idea of other authors and historians, that the major difference between Einstein and his predecessors is Einstein's rejection of the aether, because, it is always possible to add for whatever reason the notion of a privileged frame to special relativity, as long as one accepts that it will remain unobservable, and also Poincaré argued that "*some day, no doubt, the aether will thrown aside as useless*". However, Brown gave some examples, what in his opinion were the new features in Einstein's work:

> p. 66: "*The full meaning of relativistic kinematics was simply not properly understood before Einstein. Nor was the 'theory of relativity' as Einstein articulated it in 1905 anticipated even in its programmatic form.*" p. 69. "*How did Albert Einstein...arrive at his special theory of relativity?...I want only to stress that it is impossible to understand Einstein's discovery (if that is the right word) of special relativity without taking on board the impacts of the quantum in physics.*" p. 81. "*In this respect [Brown refers to the conventional nature of distant simultaneity] Einstein was doing little more than expanding on a theme that Poincaré had already introduced. Where Einstein goes well beyond the great mathematician is in his treatment of the coordinate transformations... In particular, the extraction of the phenomena of length contraction and time dilation directly from the Lorentz transformations in section 4 of the 1905 paper is completely original.*"

After that, Brown develops his own dynamical interpretation of special relativity as opposed to the kinematical approach of Einstein's 1905 paper (although he says that this dynamical view is already contained in Einstein's 1905-paper, "*masqueraded in the language of kinematics*", p. 82), and the modern understanding of space-time.

Roger Cerf (2006)

Roger Cerf (2006)[] gave priority to Einstein for developing special relativity, and criticized the assertions of Leveugle and others concerning the priority of Poincaré. While Cerf agreed that Poincaré made important contributions to relativity, he argued (following Pais) that Poincaré "*stopped short before the crucial step*" because he handled length contraction as a "third hypothesis", therefore Poincaré lacked a complete understanding of the basic principles of relativity. "*Einstein's crucial step was that he abandoned the mechanistic ether in favor of a new kinematics.*" He also denies the idea, that Poincaré invented E=mc² in its modern relativistic sense, because he did not realize the implications of this relationship. Cerf considers Leveugle's Hilbert-Planck-Einstein connection an implausible conspiracy theory.

Shaul Katzir (2005)

Katzir (2005)[] argued that "*Poincaré's work should not be seen as an attempt to formulate special relativity, but as an independent attempt to resolve questions in electrodynamics.*" Contrary to Miller and others, Katzir thinks that Poincaré's development of electrodynamics led him to the rejection of the pure electromagnetic world-view (due to the non-electromagnetic Poincaré-Stresses introduced in 1905), and Poincaré's theory represents a "*relativistic physics*" which is guided by the relativity principle. In this physics, however, "*Lorentz's theory and Newton's theory remained as the fundamental bases of electrodynamics and gravitation*."

Scott Walter (2005, 2007)

Walter (2005) argues that both Poincaré and Einstein put forward the theory of relativity in 1905. And in 2007 he wrote, that although Poincaré formally introduced four-dimensional spacetime in 1905/6, he was still clinging to the idea of "Galilei spacetime". That is, Poincaré preferred Lorentz covariance over Galilei covariance when it is about phenomena accessible to experimental tests; yet in terms of space and time, Poincaré preferred Galilei spacetime over Minkowski spacetime, and length contraction and time dilation "*are merely apparent phenomena due to motion with respect to the ether*". This is the fundamental difference in the two principal approaches to relativity theory, namely that of "Lorentz and Poincaré" on one side, and "Einstein and Minkowski" on the other side.[]

General relativity

E.T. Whittaker

Whittaker (1954)[36] stated that David Hilbert had derived the theory of General Relativity from an elegant variational principle *almost simultaneously* with Einstein's discovery of the theory.

Albrecht Fölsing on the Hilbert-Einstein interaction (1993)

From Fölsing's 1993 (English translation 1998)[31] Einstein biography (footnote references in the quote are from the original text and the actual notes are not reproduced here):

> During the decisive phase Einstein even had a congenial colleague, though this caused him more annoyance than joy, as it seemed to threaten his primacy. "Only one colleague truly understood it, and he now tries skillfully to appropriate it."[29] he complained to Zangger about what he evidently regarded as an attempt at plagiarism. This colleague was none other than David Hilbert, with whom, as recently as the summer, Einstein had been "absolutely delighted." What must have irritated Einstein was that Hilbert had published the correct field equations first—a few days before Einstein.

Einstein presented his equations in Berlin on November 25, 1915, but six days earlier, on November 20, Hilbert—had derived the identical field equations for which Einstein had been searching such a long time.[31] How had this happened?

David Hilbert had concerned himself intensively with physics for a number of years; had read everything about electrons, matter, and fields: and in this context had invited Einstein to Göttingen toward the end of June 1915 to lecture on relativity theory. Einstein had stayed at the Hilberts' home, and one must assume that the week he and Hilbert spent together would have consisted of dawn-to-dusk discussions of physics. They continued their debate in writing, although Felix Klein records that "they talked past one another, as happens not infrequently between simultaneously producing mathematicians."[32] Hilbert was in fact aiming at greater things than Einstein: at a theory of the entire physical world, of matter and fields, of universe and electrons—and in a strictly axiomatic structure.

In November, when Einstein was totally absorbed in his theory of gravitation, he essentially corresponded only with Hilbert, sending Hilbert his publications and, on November 18, thanking him for a draft of his treatise. Einstein must have received that treatise immediately before writing this letter. Could Einstein, casting his eye over Hilbert's paper, have discovered the term which was still lacking in his own equations, and thus "appropriated" Hilbert? This is not really probable: Hilbert's treatise was exceedingly involved, or indeed confused—according to Felix Klein, it was the kind of work "that no one understands unless he has already mastered the whole subject."[33] It cannot be entirely ruled out that Hilbert's treatise made Einstein aware of some weakness in his own equations. Nevertheless, his eventual derivation of the equations was a logical development of his earlier arguments—in which, despite all the mathematics, physical principles invariably predominated. His approach was thus quite different from Hilbert's, and Einstein's achievements can, therefore, surely be regarded as authentic.

For a few weeks relations between Einstein and Hilbert were clouded; at least, we know that Einstein was convinced that his Göttingen lectures and some of his other thoughts had—perhaps inadvertently—been plagiarized by Hilbert. It may well be, though, that he was somewhat mollified when he saw the printed version of Hilbert's treatise, since Hilbert, in the very first sentence, paid tribute to "the gigantic problems raised by Einstein and the brilliant methods developed by him for their solution,"[34] which represented the prerequisites of a new approach to the fundamentals of physics. Thirty years later, Einstein told his assistant Ernst G. Straus, who in turn after another thirty years told Abraham Pais, that "Hilbert had sent him a written apology, informing him that he had 'quite forgotten that lecture.' "[35] If that is what happened, then it must have satisfied Einstein, for just before Christmas he wrote to Hilbert: "There has been between us something like a bad feeling, the cause of which I don't wish to analyze further. I struggled against a resulting sense of bitterness, and I did so with complete success. I once more think of you in unclouded friendship, and would ask you to try to do likewise toward me. It is, objectively speaking, a pity if two fellows who have worked their way out of this shabby world cannot find pleasure in one another."[36] The reconciliation worked so well that no one else seems to have noticed any friction, and a legend arose that there had never been anything but friendly feelings between Einstein and Hilbert.[37] Hilbert, like all his other colleagues, acknowledged Einstein as the sole creator of relativity theory.

Cory/Renn/Stachel and Friedwardt Winterberg (1997/2003)

In 1997, Cory, Renn and Stachel published a 3-page article in *Science* entitled "Belated Decision in the Hilbert-Einstein Priority Dispute" [45], concluding that Hilbert had not anticipated Einstein's equations.[32][46]

Friedwardt Winterberg,[47] a professor of physics at the University of Nevada, Reno, disputed [48] these conclusions, observing that the galley proofs of Hilbert's articles had been tampered with - part of one page had been cut off. He goes on to argue that the removed part of the article contained the equations that Einstein later published, and he wrote that *the cut off part of the proofs suggests a crude attempt by someone to falsify the historical record.* "Science" declined to publish this; it was printed in revised form in "Zeitschrift für Naturforschung", with a dateline of June 5, 2003. Winterberg wrote that the correct field equations are still present on the existing pages of the proofs in various equivalent forms. In this paper Winterberg asserted that Einstein *sought the help of* Hilbert and Klein to help him find the *correct field equation*, without mentioning the research of Fölsing (1997) and Sauer (1999) according to which Hilbert *invited* Einstein to Göttingen to give a week of lectures on general relativity in June 1915, which however does not necessarily contradict Winterberg. Hilbert at the time was looking for physics problems to solve.

A short reply to Winterberg's article could be found at [49]; the original long reply can be accessed via the Internet Archive at [50]. In this reply, Winterberg's hypothesis is called "paranoid" and "speculative". Cory et al. offer the following alternative speculation: "it is possible that Hilbert himself cropped off the top of p. 7 to include it with the three sheets he sent Klein, in order that they not end in mid-sentence."[51]

As of September 2006, the Max Planck Institute of Berlin has replaced the short reply with a note [52] saying that the society "distances itself from statements published on this website [...] concerning Prof. Friedwart Winterberg" and stating that "the Max Planck Institute will not take a position in [this] scientific dispute".

Ivan Todorov, in a paper published on ArXiv,[33] says of the debate:

> Their [CRS's] attempt to support on this ground Einstein’s accusation of “nostrification” goes much too far. A calm, non-confrontational reaction was soon provided by a thorough study[30] of Hilbert’s route to the “Foundations of Physics” (see also the relatively even handed survey (Viz 01)).

In the paper recommended by Todorov as calm and non-confrontational, Tilman Sauer[30] concludes that the printer's proofs show conclusively that Einstein did not plagiarize Hilbert, stating

> any possibility that Einstein took the clue for the final step toward his field equations from Hilbert's note [Nov 20, 1915] is now definitely precluded.

Max Born's letters to David Hilbert, quoted in Wuensch, is quoted by Todorov as evidence that Einstein's thinking towards general covariance was influenced by the competition with Hilbert.

Todorov ends his paper by stating:

> Einstein and Hilbert had the moral strength and wisdom - after a month of intense competition, from which, in a final account, everybody (including science itself) profited - to avoid a lifelong priority dispute (something in which Leibniz and Newton failed). It would be a shame to subsequent generations of scientists and historians of science to try to undo their achievement.

Anatoly Alexeevich Logunov on general relativity (2004)

Anatoly Logunov is a former Vice President of the Soviet Academy of Sciences and currently the Scientific advisor of the Institute for High Energy Physics.[53][54] Author of a book about Poincaré's relativity theory [55]. Coauthor, with Mestvirishvili and Petrov, of an article rejecting the conclusions of the Corry/Renn/Stachel paper. They discuss both Einstein's and Hilbert's papers, claiming that Einstein and Hilbert arrived at the correct field equations independently. Specifically, they conclude that:

> *Their pathways were different but they led exactly to the same result. Nobody "nostrified" the other. So no “belated decision in the Einstein–Hilbert priority dispute”, about which [Corry, Renn, and Stachel] wrote, can*

> *be taken. Moreover, the very Einstein–Hilbert dispute never took place.*
>
> *All is absolutely clear: both authors made everything to immortalize their names in the title of the gravitational field equations. But general relativity is Einstein's theory.*[56]

Wuensch and Sommer (2005)

Daniela Wuensch,[10] a historian of science and a Hilbert and Kaluza expert, responded to Bjerknes, Winterberg and Logunov's criticisms of the Corry/Renn/Stachel paper in a book which appeared in 2005 [57], wherein she defends the view that the cut to Hilbert's printer proofs was made in recent times. Moreover, she presents a theory about what might have been on the missing part of the proofs, based upon her knowledge of Hilbert's papers and lectures.

She defends the view that knowledge of Hilbert's November 16, 1915 letter was crucial to Einstein's development of the field equations: Einstein arrived at the correct field equations only with Hilbert's help ("nach großer Anstrengung mit Hilfe Hilberts"), but nevertheless calls Einstein's reaction (his negative comments on Hilbert in the November 26 letter to Zangger) "understandable" ("Einsteins Reaktion ist verständlich") because Einstein had worked on the problem for a long time.

According to her publisher, Klaus Sommer, Wuensch concludes though that:

> This comprehensive study concludes with a historical interpretation. It shows that while it is true that Hilbert must be seen as the one who first discovered the field equations, the general theory of relativity is indeed Einstein's achievement, whereas Hilbert developed a unified theory of gravitation and electromagnetism. [57]

In 2006, Wuensch was invited to give a talk at the annual meeting of the German Physics Society (Deutsche Physikalische Gesellschaft) about her views about the priority issue for the field equations.[58]

Wuensch's publisher, Klaus Sommer, in an article in "Physik in unserer Zeit",[59] supported Wuensch's view that Einstein obtained some results not independently but from the information obtained from Hilbert's November 16 letter and from the notes of Hilbert's talk. While he does not call Einstein a plagiarist, Sommer speculates that Einstein's conciliatory December 20 letter was motivated by the fear that Hilbert might comment on Einstein's behaviour in the final version of his paper, claiming that a scandal caused by Hilbert could have done more damage to Einstein than any scandal before ("Ein Skandal Hilberts hätte ihm mehr geschadet als jeder andere zuvor").

David E. Rowe (2006)

The contentions of Wuensch and Sommer have been strongly contested by the historian of mathematics and natural sciences David E. Rowe in a detailed review of Wuensch's book published in *Historia Mathematica* in 2006.[60] Rowe argues that Wuensch's book offers nothing but tendentious, unsubstantiated, and in many cases highly implausible, speculations.

Footnotes

[1] On Mileva Marić's alleged contributions, see The Einstein Controversy (http://physicsbuzz.physicscentral.com/2008/12/einstein-controversy.html), Physics Central, 17 December 2008.

[2] [Poi02]

[3] [Sta89], p. 893, footnote 10

[4] [Ein05d], last section

[5] Einstein, Albert: "Ether and the Theory of Relativity" (1920), republished in *Sidelights on Relativity* (Methuen, London, 1922)

[6] , Extract of page 318 (http://books.google.com/books?id=cdxWNE7NY6QC&pg=PA318)

[7] http://termessos.de/prooffotos.htm

[8] D. Hilbert, *Nac. Ges. Wiss. Goettingen* 1916, 395, cited in [Cor97].

[9] [Hil24] page 2

[10] Daniela Wuensch, *"zwei wirkliche Kerle", Neues zur Entdeckung der Gravitationsgleichungen der Allgemeinen Relativitätstheorie durch Einstein und Hilbert.* Termessos, 2005, ISBN 3-938016-04-3

[11] Whittaker (1953), pp. 27-77

[13] .

[15] (thesis)

[17] Renn, J.,: Albert Einstein in den Annalen der Physik (http://einstein-annalen.mpiwg-berlin.mpg.de/home), 2005

[18] The titles of 21 reviews written in 1905 can be found in "The Collected Papers of Albert Einstein, Volume 2". See online (http://press.princeton.edu/TOCs/c4453.html).

[20] . See also English translation

[21] . **English translation**:

[22] Martinez (2009)

[25] .

[26] Kip Thorne (1994): *Black Holes and Time Warps: Einstein's Outrageous Legacy*, W. W. Norton & Company; Reprint edition (January 1995). ISBN 0-393-31276-3

[27] Mehra, J. (1974) "Einstein, Hilbert, and the Theory of Gravitation" Reidel, Dordrecht, Netherlands.

[28] : Author's site (http://home.comcast.net/~xtxinc/AEGRBook.htm)

[29] [Hil24] English translation from Bje03a, p. 17;]

[30] Tilman Sauer, "The relativity of discovery: Hilbert's first note on the foundations of physics", Arch. Hist. Exact Sci., **v53**, 529-575 (1999)

[31] Fölsing, Albrecht: *Einstein - a biography*; Penguin (Non-Classics); New Ed edition (June 1, 1998). ISBN 0-14-023719-4.

[32] Leo Corry, Jürgen Renn, John Stachel: "Belated Decision in the Hilbert-Einstein Priority Dispute", SCIENCE, Vol. 278, 14 November 1997 - article text (http://www.tau.ac.il/~corry/publications/articles/science.html)

[33] Todorov, Ivan T., *Einstein and Hilbert: The Creation of General Relativity*, Institut fuer Theoretische Physik Universitaet Goettingen, , 25 April 2005.

[34] Logunov, A. A (2004): "Henri Poincaré and Relativity Theory" - Phys. Usp. 47 (2004) 607-621; Usp. Fiz. Nauk 174 (2004) 663-678 - PraXis 2004 abstract (http://arxiv.org/abs/physics/0405075) - PDF (http://arxiv.org/pdf/physics/0408077)

[35] Jürgen Renn und Tilman Sauer (1996), "Einsteins Züricher Notizbuch: Die Entdeckung der Feldgleichungen der Gravitation im Jahre 1912", preprint 28 from Max Planck Institute - Web link (http://www.mpiwg-berlin.mpg.de/Preprints/28/Preprint_28_Title.html). Publication date implied from web directory.

[36] Whittaker, E. T (1953) *A History of the Theories of Aether and Electricity: Vol 2 The Modern Theories 1900-1926. Chapter II: The Relativity Theory of Poincaré and Lorentz*, Nelson, London.

[37] Keswani, G. H. (1965-6) "Origin and Concept of Relativity, Parts I, II, III", Brit. J. Phil. Sci., v15-17. *British Journal for the Philosophy of Science*, .

[38] Herbert Dingle, "Note on Mr Keswani's articles, Origin and Concept of Relativity", Brit. J. Phil. Sci., vol 16, No 63 (Nov 1965), 242-246 (a response to [Kes65])

[39] Karl R. Popper, "A Note on the Difference Between the Lorentz-Fitzgerald Contraction and the Einstein Contraction", Br. J. Phil. Sci. 16:64 (Feb 1966): 332-333 (a response to [Kes65])

[40] Keswani, G. H. (1966), "Reply to Professor Dingle and Mr Levinson", Brit. J. Phil. Sci., Vol. 17, No. 2 (Aug 1966), 149-152 (a response to [Din65])

[41] Keswani, G. H. (1966), "Origin and Concept of Relativity: Reply to Professor Popper", Brit. J. Phil. Sci, Vol 17 no 3 (Nov 1966), 234-236 (a response to [Pop65]

[42] http://www.aip.org/history/einstein/essay-einsteins-time.htm

[43] Author's site (http://home.comcast.net/~xtxinc/AEIPBook.htm)

[44] Harvey R. Brown, Physical relativity: space-time structure from a dynamical perspective. Oxford University Press, 2005.

[45] http://www.garfield.library.upenn.edu/histcomp/einstein-a_all-w-citing-pre-56_e/node/12342.html

[46] Jürgen Renn and John Stachel, *Hilbert's Foundation of Physics: From a Theory of Everything to a Constituent of General Relativity* - can be downloaded from link 118 in the preprint list at Max Planck Institute (http://www.mpiwg-berlin.mpg.de/Preprints/P118.PDF).

[47] Friedwart Winterberg: a critique (http://physics.unr.edu/faculty/winterberg/Hilbert-Einstein.pdf) of [Cor97] as printed in "Zeitschrift für Naturforschung" 59a (http://www.znaturforsch.com/c59a.htm), 715-719.

[48] http://web.archive.org/web/20070629183442/http://physics.unr.edu/faculty/winterberg/Hilbert-Einstein.pdf

[49] http://www.mpiwg-berlin.mpg.de/texts/Winterberg-Antwort.pdf

[50] http://web.archive.org/web/20050313161944/http://www.mpiwg-berlin.mpg.de/texts/Winterberg-Antwort.html

[51] Corry, Renn Stachel: Short response (http://www.mpiwg-berlin.mpg.de/texts/Winterberg-Antwort.pdf) to [Win02] - note: the original response was later replaced with a shorter one, and on September 14, 2006, this was replaced with a statement stating that the Max Planck Institute distances itself from Corry et al.'s statements about Winterberg. The original two versions are no longer available at this URL or at the Wayback Machine.

[52] http://www.mpiwg-berlin.mpg.de/texts/Winterberg-Antwort.html

[53] http://www.biograph.comstar.ru/bank/logunov.htm

[54] http://www.ihep.su/ihep/info/contact.htm

[55] http://arxiv.org/abs/physics/0408077

[56] A.A. Logunov, M.A.Mestvirishvili, V.A. Petrov (2004): How Were the Hilbert-Einstein Equations Discovered? Phys.Usp. 47 (2004) 607-621; Usp.Fiz.Nauk 174 (2004) 663-678,

[57] http://termessos.de/einsteinhilbertdispute.htm

[58] http://www.dpg-tagungen.de/program/muenchen/gr302.pdf

[59] Sommer, Klaus: "Wer entdeckte die Allgemeine Relativitätstheorie? Prioritätsstreit zwischen Hilbert und Einstein", Physik in unserer Zeit Volume 36, Issue 5, Pages 230 - 235. Published Online: 29 Aug 2005. Available online from Wiley InterScience (http://www3.interscience.wiley.com/cgi-bin/abstract/111083634/ABSTRACT?CRETRY=1&SRETRY=0) (expect some problems; paid access to text only)

[60] David E. Rowe, Review of Daniela Wuensch's *Zwei Wirkliche Kerle*, *Historia Mathematica*, vol. 33, Issue 4, November 2006, pp. 500-508. http://www.sciencedirect.com/science/article/pii/S0315086005000509

References

Works of physics (primary sources)

[Ein05c]

Albert Einstein: *Zur Elektrodynamik bewegter Körper*, Annalen der Physik 17(1905), 891-921. Received June 30, published September 26, 1905. Reprinted with comments in [Sta89], p. 276-306 English translation, with footnotes not present in the 1905 paper, available on the net (http://www.fourmilab.ch/etexts/einstein/specrel/)

[Ein05d]

Albert Einstein: *Ist die Trägheit eines Körpers von seinem Energiegehalt abhängig?*, Annalen der Physik 18(1905), 639-641, Reprinted with comments in [Sta89], Document 24 English translation available on the net (http://www.fourmilab.ch/etexts/einstein/E_mc2/)

[Ein06]

Albert Einstein: *Das Prinzip von der Erhaltung der Schwerpunktsbewegung und die Trägheit der Energie* Annalen der Physik 20(1906):627-633, Reprinted with comments in [Sta89], Document 35

[Ein15a]

Einstein, A. (1915) "Die Feldgleichungun der Gravitation". *Sitzungsberichte der Preussischen Akademie der Wissenschaften zu Berlin*, 844-847.

[Ein15b]

Einstein, A. (1915) "Zur allgemeinen Relativatstheorie", *Sitzungsberichte der Preussischen Akademie der Wissenschaften zu Berlin*, 778-786

[Ein15c]

Einstein, A. (1915) "Erklarung der Perihelbewegung des Merkur aus der allgemeinen Relatvitatstheorie", *Sitzungsberichte der Preussischen Akademie der Wissenschaften zu Berlin*, 799-801

[Ein15d]

Einstein, A. (1915) "Zur allgemeinen Relativatstheorie", *Sitzungsberichte der Preussischen Akademie der Wissenschaften zu Berlin*, 831-839

[Ein16]

Einstein, A. (1916) "Die Grundlage der allgemeinen Relativitätstheorie", *Annalen der Physik*, 49

[Hil24]

Hilbert, D., *Die Grundlagen der Physik* - *Mathematische Annalen*, 92, 1924 - "meiner theorie" quote on page 2 - online at Uni Göttingen (http://dz-srv1.sub.uni-goettingen.de/sub/digbib/loader?ht=VIEW&did=D29243) - index of journal (http://dz-srv1.sub.uni-goettingen.de/cache/toc/D29239.html)

[Lan05]

Langevin, P. (1905) "Sur l'origine des radiations et l'inertie électromagnétique", *Journal de Physique Théorique et Appliquée*, **4**, pp. 165–183.

[Lan14]

Langevin, P. (1914) "Le Physicien" in *Henri Poincaré Librairie* (Felix Alcan 1914) pp. 115–202.

[Lor99]

Lorentz, H. A. (1899) "Simplified Theory of Electrical and Optical Phenomena in Moving Systems", *Proc. Acad. Science Amsterdam*, **I**, 427-43.

[Lor04]

Lorentz, H. A. (1904) "Electromagnetic Phenomena in a System Moving with Any Velocity Less Than That of Light", *Proc. Acad. Science Amsterdam*, **IV**, 669-78.

[Lor11]

Lorentz, H. A. (1911) *Amsterdam Versl.* **XX**, 87

[Lor14]

Lorentz, H. A. (1914) "Two Papers of Henri Poincaré on Mathematical Physics," *Acta Mathematica 38*: 293, p. 1921.

[Pla07]

Planck, M. (1907) *Berlin Sitz.*, 542

[Pla08]

Planck, M. (1908) *Verh. d. Deutsch. Phys. Ges.* **X**, p218, and *Phys. ZS*, **IX**, 828

[Poi89]

Poincaré, H. (1889) *Théorie mathématique de la lumière*, Carré & C. Naud, Paris. Partly reprinted in [Poi02], Ch. 12.

[Poi97]

Poincaré, H. (1897) "The Relativity of Space" (http://www.marxists.org/reference/subject/philosophy/works/fr/poincare.htm), article in English translation

[Poi00]

Poincaré, Henri (1900), "La théorie de Lorentz et le principe de réaction", *Archives néerlandaises des sciences exactes et naturelles* **5**: 252–278. See also the English translation (http://www.physicsinsights.org/poincare-1900.pdf)

[Poi02]

Poincaré, Henri (1902), *Science and Hypothesis*, London and Newcastle-on-Cyne (1905): The Walter Scott publishing Co.

[Poi04]

Poincaré, Henri (1904), "L'état actuel et l'avenir de la physique mathématique", *Bulletin des Sciences Mathématiques* **28** (2): 302–324 English translation as The Principles of Mathematical Physics, in "The value of science" (1905a), Ch. 7-9.

[Poi05]

Poincaré, Henri (1905), "On the Dynamics of the Electron", *Comptes Rendus* **140**: 1504–1508

[Poi06a]

Poincaré, Henri (1906), "On the Dynamics of the Electron", *Rendiconti del Circolo matematico di Palermo* **21**: 129–176, doi: 10.1007/BF03013466 (http://dx.doi.org/10.1007/BF03013466)

[Poi08]

Poincaré, Henri (1908), *Science and Method* (http://www.archive.org/details/sciencemethod00poinuoft), London: Nelson & Sons

[Poi13]

Poincaré, Henri (1913), *Last Essays* (http://www.archive.org/details/mathematicsandsc001861mbp), New York: Dover Publication (1963)

[Ein20]

Albert Einstein: "Ether and the Theory of Relativity", An Address delivered on May 5, 1920, in the University of Leyden.

[Sta89]

John Stachel (Ed.), *The collected papers of Albert Einstein*, volume 2, Princeton University Press, 1989

Secondary sources

- Ives, H. E. (1952). "Derivation of the Mass-Energy Relationship". *J. Opt. Soc. Amer.* **42**: 540–3.
- Ives, H. E. (1953). "Note on 'Mass-Energy Relationship'". *J. O. S. A.* **43**: 619.
- Keswani, G. H., Kilmister, C. W. (1983). "Initimations of relativity. Relativity before Einstein". *British Journal for the Philosophy of Science* **34**: 343–54. ISSN 0007-0882 (http://www.worldcat.org/issn/0007-0882).
- Macrossan, M. N. (1986). "A Note on Relativity Before Einstein" (http://espace.library.uq.edu.au/view.php?pid=UQ:9560). *British Journal for the Philosophy of Science* **37**: 232–34.
- Norton, John D (1993). "General covariance and the foundations of general relativity: eight decades of dispute" (http://www.pitt.edu/~jdnorton/papers/decades.pdf) (PDF). *Rep. Prog. Phys.* **56**: 791458.
- Rothman, Tony (March/April 2006), "Lost in Einstein's Shadow" (http://www.americanscientist.org/template/AssetDetail/assetid/49611?&print=yes), *American Scientist* **94** (2): 112, doi: 10.1511/2006.2.112 (http://dx.doi.org/10.1511/2006.2.112). Wikipedia:Link rot

Unified field theory

Classical unified field theories

Since the 19th century, some physicists have attempted to develop a single theoretical framework that can account for the fundamental forces of nature – a unified field theory. **Classical unified field theories** are attempts to create a unified field theory based on classical physics. In particular, unification of gravitation and electromagnetism was actively pursued by several physicists and mathematicians in the years between World War I and World War II. This work spurred the purely mathematical development of differential geometry. Albert Einstein is the best known of the many physicists who attempted to develop a classical unified field theory.

This article describes various attempts at a classical (non-quantum), relativistic unified field theory. For a survey of classical relativistic field theories of gravitation that have been motivated by theoretical concerns other than unification, see Classical theories of gravitation. For a survey of current work toward creating a quantum theory of gravitation, see quantum gravity.

Early work

The first attempts to provide a unified theory were by G. Mie in 1912 and Ernst Reichenbacher in 1916.[1][2] However, these theories were unsatisfactory, as they did not incorporate general relativity – in the former case, because general relativity had yet to be formulated. These efforts, along with those of Forster, involved making the metric tensor (which had previously been assumed to be symmetric and real-valued) into an asymmetric and/or complex-valued tensor, and they also attempted to create a field theory for matter as well.

Differential geometry and field theory

From 1918 until 1923, there were three distinct approaches to field theory: the gauge theory of Weyl, Kaluza's five-dimensional theory, and Eddington's development of affine geometry. Einstein corresponded with these researchers, and collaborated with Kaluza, but was not yet fully involved in the unification effort.

Weyl's infinitesimal geometry

In order to include electromagnetism into the geometry of general relativity, Hermann Weyl worked to generalize the Riemannian geometry upon which general relativity is based. His idea was to create a more general infinitesimal geometry. He noted that in addition to a metric field there could be additional degrees of freedom along a path between two points in a manifold, and he tried to exploit this by introducing a basic method for comparison of local size measures along such a path, in terms of a gauge field. This geometry generalized Riemannian geometry in that there was a vector field Q, in addition to the metric g, which together gave rise to both the electromagnetic and gravitational fields. This theory was mathematically sound, albeit complicated, resulting in difficult and high-order field equations. The critical mathematical ingredients in this theory, the Lagrangians and curvature tensor, were worked out by Weyl and colleagues. Then Weyl carried out an extensive correspondence with Einstein and others as to its physical validity, and the theory was ultimately found to be physically unreasonable. However, Weyl's principle of gauge invariance was later applied in a modified form to quantum field theory.

Kaluza's fifth dimension

Kaluza's approach to unification was to embed space-time into a five-dimensional cylindrical world; one of four space dimensions and one of time. Unlike Weyl's approach, Riemannian geometry was maintained, and the extra dimension allowed for the incorporation of the electromagnetic field vector into the geometry. Despite the relative mathematical elegance of this approach, in collaboration with Einstein and Einstein's aide Grommer it was determined that this theory did not admit a non-singular, static, spherically symmetric solution. This theory did have some influence on Einstein's later work and was further developed later by Klein in an attempt to incorporate relativity into quantum theory, in what is now known as Kaluza-Klein theory.

Eddington's affine geometry

Sir Arthur Stanley Eddington was a noted astronomer who became an enthusiastic and influential promoter of Einstein's general theory of relativity. He was among the first to propose an extension of the gravitational theory based on the affine connection as the fundamental structure field rather than the metric tensor which was the original focus of general relativity. Affine connection is the basis for *parallel transport* of vectors from one space-time point to another; Eddington assumed the affine connection to be symmetric in its covariant indices, because it seemed plausible that the result of parallel-transporting one infinitesimal vector along another should produce the same result as transporting the second along the first. (Later workers revisited this assumption.)

Eddington emphasized what he considered to be epistemological considerations; for example, he thought that the cosmological constant version of the general-relativistic field equation expressed the property that the universe was "self-gauging". Since the simplest cosmological model (the De Sitter universe) that solves that equation is a spherically symmetric, stationary, closed universe (exhibiting a cosmological red shift, which is more conventionally interpreted as due to expansion), it seemed to explain the overall form of the universe.

Like many other classical unified field theorists, Eddington considered that in the Einstein field equations for general relativity the stress-energy tensor $T_{\mu\nu}$, which represents matter/energy, was merely provisional, and that in a truly unified theory the source term would automatically arise as some aspect of the free-space field equations. He also shared the hope that an improved fundamental theory would explain why the two elementary particles then known (proton and electron) have quite different masses.

The Dirac equation for the relativistic quantum electron caused Eddington to rethink his previous conviction that fundamental physical theory had to be based on tensors. He subsequently devoted his efforts into development of a "Fundamental Theory" based largely on algebraic notions (which he called "E-frames"). Unfortunately his descriptions of this theory were sketchy and difficult to understand, so very few physicists followed up on his work.[]

Einstein's geometric approaches

When the equivalent of Maxwell's equations for electromagnetism is formulated within the framework of Einstein's theory of general relativity, the electromagnetic field energy (being equivalent to mass as one would expect from Einstein's famous equation $E=mc^2$) contributes to the stress tensor and thus to the curvature of space-time, which is the general-relativistic representation of the gravitational field; or putting it another way, certain configurations of curved space-time *incorporate* effects of an electromagnetic field. This suggests that a purely geometric theory ought to treat these two fields as different aspects of the same basic phenomenon. However, ordinary Riemannian geometry is unable to describe the properties of the electromagnetic field as a purely geometric phenomenon.

Einstein tried to form a generalized theory of gravitation that would unify the gravitational and electromagnetic forces (and perhaps others), guided by a belief in a single origin for the entire set of physical laws. These attempts initially concentrated on additional geometric notions such as vierbeins and "distant parallelism", but eventually centered around treating both the metric tensor and the affine connection as fundamental fields. (Because they are not independent, the metric-affine theory was somewhat complicated.) In general relativity, these fields are symmetric (in the matrix sense), but since antisymmetry seemed essential for electromagnetism, the symmetry requirement was relaxed for one or both fields. Einstein's proposed unified-field equations (fundamental laws of physics) were generally derived from a variational principle expressed in terms of the Riemann curvature tensor for the presumed space-time manifold.[3]

In field theories of this kind, particles appear as limited regions in space-time in which the field strength or the energy density are particularly high. Einstein and coworker Leopold Infeld managed to demonstrate that, in Einstein's final theory of the unified field, true singularities of the field did have trajectories resembling point particles. However, singularities are places where the equations break down, and Einstein believed that in an ultimate theory the laws should apply *everywhere*, with particles being soliton-like solutions to the (highly nonlinear) field equations. Further, the large-scale topology of the universe should impose restrictions on the solutions, such as quantization or discrete symmetries.

The degree of abstraction, combined with a relative lack of good mathematical tools for analyzing nonlinear equation systems, make it hard to connect such theories with the physical phenomena that they might describe. For example, it has been suggested that the torsion (antisymmetric part of the affine connection) might be related to isospin rather than electromagnetism; this is related to a discrete (or *"internal"*) symmetry known to Einstein as "displacement field duality".

Einstein became increasingly isolated in his research on a generalized theory of gravitation, and most physicists consider his attempts ultimately unsuccessful. In particular, his pursuit of a unification of the fundamental forces ignored developments in quantum physics (and vice versa), most notably the discovery of the strong nuclear force and weak nuclear force.[4]

Schrödinger's pure-affine theory

Inspired by Einstein's approach to a unified field theory and Eddington's idea of the affine connection as the sole basis for differential geometric structure for space-time, Erwin Schrödinger from 1940 to 1951 thoroughly investigated pure-affine formulations of generalized gravitational theory. Although he initially assumed a symmetric affine connection, like Einstein he later considered the nonsymmetric field.

Schrödinger's most striking discovery during this work was that the metric tensor was *induced* upon the manifold via a simple construction from the Riemann curvature tensor, which was in turn formed entirely from the affine connection. Further, taking this approach with the simplest feasible basis for the variational principle resulted in a field equation having the form of Einstein's general-relativistic field equation with a cosmological term arising *automatically*.[]

Skepticism from Einstein and published criticisms from other physicists discouraged Schrödinger, and his work in this area has been largely ignored.

Later work

After the 1930s, progressively fewer scientists worked on classical unification, due to the continual development of quantum theory and the difficulties encountered in developing a quantum theory of gravity. Einstein continued to work on unified field theories of gravity and electromagnetism, but he became increasingly isolated in this research, which he pursued until his death. Despite the publicity of this work due to Einstein's celebrity status, it never resulted in a resounding success.

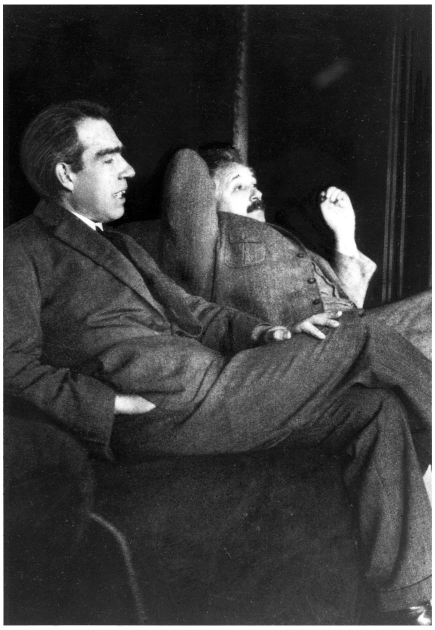
Most scientists, though not Einstein, eventually abandoned classical theories. Current mainstream research on unified field theories focuses on the problem of creating quantum gravity and unifying such a theory with the other fundamental theories in physics, which are quantum theories. (Some programs, most notably string theory, attempt to solve both of these problems at once.) With four fundamental forces now identified, gravity remains the one force whose unification proves problematic.

Although new "classical" unified field theories continue to be proposed from time to time, often involving non-traditional elements such as spinors, none has been generally accepted by physicists.

References

Collaboration and conflict

Bohr–Einstein debates



Niels Bohr with Albert Einstein at Paul Ehrenfest's home in Leiden (December 1925)

The **Bohr–Einstein debates** were a series of public disputes about quantum mechanics between Albert Einstein and Niels Bohr, who were two of its founders. Their debates are remembered because of their importance to the philosophy of science. An account of the debates has been written by Bohr in an article titled "Discussions with Einstein on Epistemological Problems in Atomic Physics".[1] Despite their differences of opinion regarding quantum mechanics, Bohr and Einstein had a mutual admiration that was to last the rest of their lives.[]

Pre-revolutionary debates

Einstein was the first physicist to say that Planck's discovery of the quantum (h) would require a rewriting of physics. As though to prove his point, in 1905 he proposed that light sometimes acts as a particle which he called a light quantum (see Photon and Wave–particle duality). Bohr was one of the most vocal opponents of the photon idea and did not openly embrace it until 1925.[2] His ability later to accept and work creatively with an idea he had so long resisted is quite unusual in the history of science. The photon appealed to Einstein because he saw it as a physical reality (although a confusing one) behind the numbers. Bohr disliked it because it made the choice of mathematical solution arbitrary. He did not like that a scientist had to choose between equations.[3]

1913 brought the Bohr model of the hydrogen atom which made use of the quantum to explain the atomic spectrum. Einstein was at first dubious, but quickly changed his mind and admitted it.

The quantum revolution

The quantum revolution of the mid-1920s occurred under the direction of both Einstein and Bohr, and their post-revolutionary debates were about making sense of the change. The shocks for Einstein began in 1925 when Werner Heisenberg introduced matrix equations that removed the Newtonian elements of space and time from any underlying reality. The next shock came in 1926 when Max Born proposed that the mechanics was to be understood as a probability without any causal explanation.

Einstein rejected this interpretation. In a 1926 letter to Max Born, Einstein wrote: "I, at any rate, am convinced that He [God] does not throw dice."[4]

Finally, in late 1927, Heisenberg and Born declared at the Solvay Conference that the revolution was over and nothing further was needed. It was at that last stage that Einstein's skepticism turned to dismay. He believed that much had been accomplished, but the reasons for the mechanics still needed to be understood.[3]

Einstein's refusal to accept the revolution as complete reflected his desire to see developed a model for the underlying causes from which these apparent random statistical methods resulted. He did not reject the idea that positions in space-time could never be completely known but did not want to allow the Uncertainty Principle to necessitate a seemingly random, non-deterministic mechanism by which the laws of physics operated. Einstein himself was a great statistical thinker but disagreed that no more needed to be discovered and clarified.[3] Bohr, meanwhile, was dismayed by none of the elements that troubled Einstein. He made his own peace with the contradictions by proposing a Principle of Complementarity that emphasized the role of the observer over the observed.[2]

Post-Revolution: First stage

As mentioned above, Einstein's position underwent significant modifications over the course of the years. In the first stage, Einstein refused to accept quantum indeterminism and sought to demonstrate that the principle of indeterminacy could be violated, suggesting ingenious *thought experiments* which should permit the accurate determination of incompatible variables, such as position and velocity, or to explicitly reveal simultaneously the wave and the particle aspects of the same process.

The first serious attack by Einstein on the "orthodox" conception took place during the *Fifth Solvay International Conference* on Electrons and Photons in 1927. Einstein pointed out how it was possible to take advantage of the (universally accepted) laws of conservation of energy and of impulse (momentum) in order to obtain information on the state of a particle in a process of interference which, according to the principle of indeterminacy or that of complementarity, should not be accessible.

In order to follow his argumentation and to evaluate Bohr's response, it is convenient to refer to the experimental apparatus illustrated in figure A. A beam of light perpendicular to the *X* axis which propagates in the direction *z* encounters a screen S_1 which presents a narrow (with respect to the wavelength of the ray) slit. After having passed through the slit, the wave function diffracts with an angular opening that causes it to encounter a second screen S_2 which presents two slits. The successive propagation of the wave results in the formation of the interference figure on the final screen *F*.

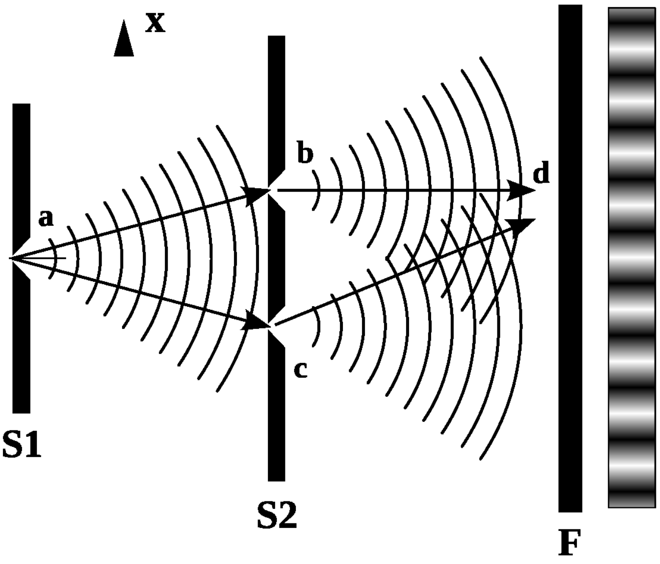
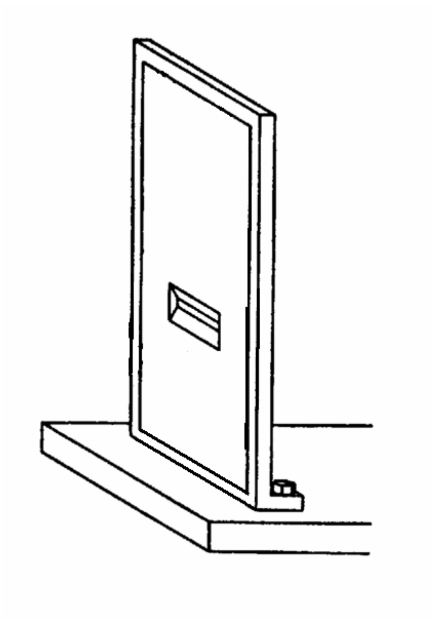


Figure A. A monochromatic beam (one for which all the particles have the same impulse) encounters a first screen, diffracts, and the diffracted wave encounters a second screen with two slits resulting in the formation of an interference figure on the background *F*. As always, it is assumed that only one particle at a time is able to pass the entire mechanism. From the measure of the recoil of the screen S_1, according to Einstein, one can deduce from which slit the particle has passed without destroying the wave aspects of the process.

At the passage through the two slits of the second screen S_2, the wave aspects of the process become essential. In fact, it is precisely the interference between the two terms of the quantum superposition corresponding to states in which the particle is localized in one of the two slits which implies that the particle is "guided" preferably into the zones of constructive interference and cannot end up in a point in the zones of destructive interference (in



Einstein's slit.

which the wave function is nullified). It is also important to note that any experiment designed to evidence the "corpuscular" aspects of the process at the passage of the screen S_2 (which, in this case, reduces to the determination of which slit the particle has passed through) inevitably destroys the wave aspects, implies the disappearance of the interference figure and the emergence of two concentrated spots of diffraction which confirm our knowledge of the trajectory followed by the particle.

At this point Einstein brings into play the first screen as well and argues as follows: since the incident particles have velocities (practically) perpendicular to the screen S_1, and since it is only the interaction with this screen that can cause a deflection from the original direction of propagation, by the law of conservation of impulse which implies that the sum of the impulses of two systems which interact is conserved, if the incident particle is deviated toward the top, the screen will recoil toward the bottom and vice-versa. In realistic conditions the mass of the screen is so heavy that it will remain stationary, but, in principle, it is possible to measure even an infinitesimal recoil. If we imagine taking the measurement of the impulse of the screen in the direction X after every single particle has passed, we can know, from the fact that the screen will be found recoiled toward the top (bottom), if the particle in question has been deviated toward the bottom (top) and therefore we can know from which slit in S_2 the particle has passed. But since the determination of the direction of the recoil of the screen after the particle has passed cannot influence the successive development of the process, we will still have an interference figure on the screen F. The interference takes place precisely because the state of the system is the *superposition* of two states whose wave functions are non-zero only near one of the two slits. On the other hand, if every particle passes through only the slit b or the slit c, then the set of systems is the statistical mixture of the two states, which means that interference is not possible. If Einstein is correct, then there is a violation of the principle of indeterminacy.

Bohr's response was to illustrate Einstein's idea more clearly via the diagram in Figure C (Figure C shows a fixed screen S1 that is bolted down. Then try to imagine one that can slide up or down along a rod instead of a fixed bolt.) Bohr observes that extremely precise knowledge of any (potential) vertical motion of the screen is an essential presupposition in Einstein's argument. In fact, if its velocity in the direction X *before* the passage of the particle is not known with a precision substantially greater than that induced by the recoil (that is, if it were already moving vertically with an unknown and greater velocity than that which it derives as a consequence of the contact with the particle), then the determination of its motion after the passage of the particle would not give the information we seek. However, Bohr continues, an extremely precise determination of the velocity of the screen, when one applies the principle of indeterminacy, implies an inevitable imprecision of its position in the direction X. Before the process even begins, the screen would therefore occupy an indeterminate position at least to a certain extent (defined by the formalism). Now consider, for example, the point d in figure A, where there is destructive interference. It's obvious that any displacement of the first screen would make the lengths of the two paths, a-b-d and a-c-d, different from those indicated in the figure. If the difference between the two paths varies by half a wavelength, at point d there will be constructive rather than destructive interference. The ideal experiment must average over all the possible positions of the screen S1, and, for every position, there corresponds, for a certain fixed point F, a different type of interference, from the perfectly destructive to the perfectly constructive. The effect of this averaging is that the pattern of interference on the screen F will be uniformly grey. Once more, our attempt to evidence the corpuscular aspects in S_2 has destroyed the possibility of interference in F which depends crucially on the wave aspects.

It should be noted that, as Bohr recognized, for the understanding of this phenomenon "it is decisive that, contrary to genuine instruments of measurement, these bodies along with the particles would constitute, in the case under examination, the system to which the quantum-mechanical formalism must apply. With respect to the precision of the conditions under which one can correctly apply the formalism, it is essential to include the entire experimental apparatus. In fact, the introduction of any new apparatus, such as a mirror, in the path of a particle could introduce new effects of interference which influence essentially the predictions about the results which will be registered at the end." Further along, Bohr attempts to resolve this ambiguity concerning which parts of the system should be considered macroscopic and which not:

> *In particular, it must be very clear that...the unambiguous use of spatiotemporal concepts in the description of atomic phenomena must be limited to the registration of observations which refer to images on a photographic lens or to analogous practically irreversible effects of amplification such as the formation of a drop of water around an ion in a dark room.*

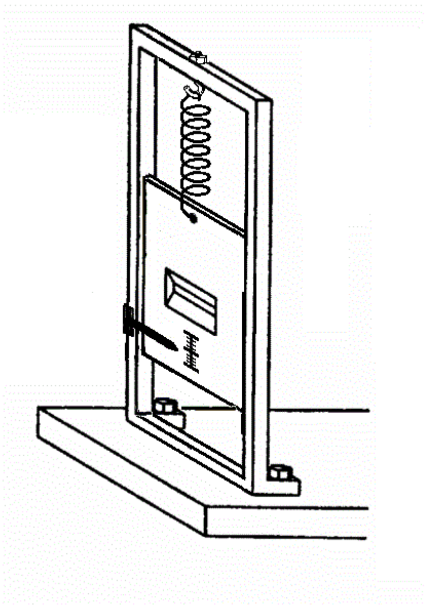


Figure C. In order to realize Einstein's proposal, it is necessary to replace the first screen in Figure A (S1) with a movable diaphragm which can move vertically such as this proposed by Bohr.

Bohr's argument about the impossibility of using the apparatus proposed by Einstein to violate the principle of indeterminacy depends crucially on the fact that a macroscopic system (the screen S_1) obeys quantum laws. On the other hand, Bohr consistently held that, in order to illustrate the microscopic aspects of reality it is necessary to set off a process of amplification which involves macroscopic apparatuses, whose fundamental characteristic is that of obeying classical laws and which can be described in classical terms. This ambiguity would later come back in the form of what is still called today the measurement problem.

The principle of indeterminacy applied to time and energy

In many textbook examples and popular discussions of quantum mechanics, the principle of indeterminacy is explained by reference to the pair of variables position and velocity (or momentum). It is important to note that the wave nature of physical processes implies that there must exist another relation of indeterminacy: that between time and energy. In order to comprehend this relation, it is convenient to refer to the experiment illustrated in Figure D, which results in the propagation of a wave which is limited in spatial extension. Assume that, as illustrated in the figure, a ray which is extremely extended longitudinally is propagated toward a screen with a slit furnished with a shutter which remains open only for a very brief interval of time Δt. Beyond the slit, there will be a wave of limited spatial extension which continues to propagate toward the right.

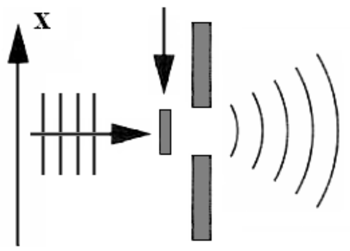


Figure D. A wave extended longitudinally passes through a slit which remains open only for a brief interval of time. Beyond the slit, there is a spatially limited wave in the direction of propagation.

A perfectly monochromatic wave (such as a musical note which cannot be divided into harmonics) has infinite spatial extent. In order to have a wave which is limited in spatial extension (which is technically called a wave packet), several waves of different frequencies must be superimposed and distributed continuously within a certain interval of frequencies around an average value, such as ν_0. It then happens that at a certain instant, there exists a spatial region (which moves over time) in which the contributions of the various fields of the superposition add up constructively. Nonetheless, according to a precise mathematical theorem, as we move far away from this region, the phases of the various fields, at any specified point, are distributed causally and destructive interference is produced. The region in which the wave has non-zero amplitude is therefore spatially limited. It is easy to demonstrate that, if the wave has a spatial extension equal to Δx (which means, in our example, that the shutter has remained open for a time $\Delta t = \Delta$ where v is the velocity of the wave), then the wave contains (or is a superposition of) various monochromatic waves whose frequencies cover an interval $\Delta\nu$ which satisfies the relation:

$$\Delta\nu \geq \frac{1}{\Delta t}.$$

Remembering that in the universal relation of Planck, frequency and energy are proportional:

$$E = h\nu$$

it follows immediately from the preceding inequality that the particle associated with the wave should possess an energy which is not perfectly defined (since different frequencies are involved in the superposition) and consequently there is indeterminacy in energy:

$$\Delta E = h\,\Delta\nu \geq \frac{h}{\Delta t}.$$

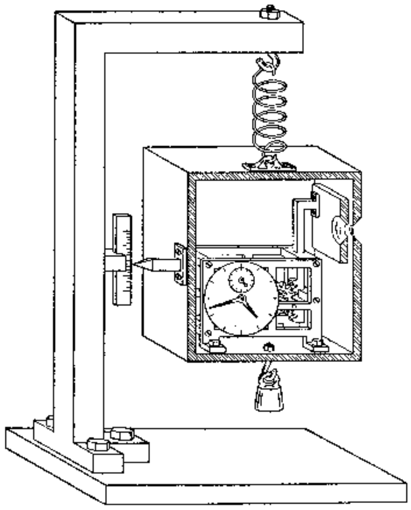
From this it follows immediately that:

$$\Delta E\,\Delta t \geq h$$

which is the relation of indeterminacy between time and energy.

Einstein's second criticism

At the sixth Congress of Solvay in 1930, the indeterminacy relation just discussed was Einstein's target of criticism. His idea contemplates the existence of an experimental apparatus which was subsequently designed by Bohr in such a way as to emphasize the essential elements and the key points which he would use in his response.

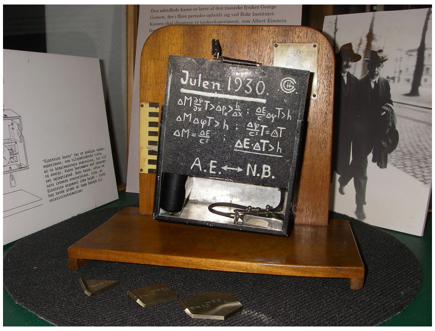


Einstein's thought experiment of 1930 as designed by Bohr. Einstein's box was supposed to prove the violation of the indeterminacy relation between time and energy.

Einstein considers a box (called **Einstein's box**; see figure) containing electromagnetic radiation and a clock which controls the opening of a shutter which covers a hole made in one of the walls of the box. The shutter uncovers the hole for a time Δt which can be chosen arbitrarily. During the opening, we are to suppose that a photon, from among those inside the box, escapes through the hole. In this way a wave of limited spatial extension has been created, following the explanation given above. In order to challenge the indeterminacy relation between time and energy, it is necessary to find a way to determine with adequate precision the energy that the photon has brought with it. At this point, Einstein turns to his celebrated relation between mass and energy of special relativity: $E = mc^2$. From this it follows that knowledge of the mass of an object provides a precise indication about its energy. The argument is therefore very simple: if one weighs the box before and after the opening of the shutter and if a certain amount of energy has escaped from the box, the box will be lighter. The variation in mass multiplied by c^2 will provide precise knowledge of the energy emitted. Moreover, the clock will indicate the precise time at which the event of the particle's emission took place. Since, in principle, the mass of the box can be determined to an arbitrary degree of accuracy, the energy emitted can be determined with a precision ΔE as accurate as one desires. Therefore, the product $\Delta E \Delta t$ can be rendered less than what is implied by the principle of indeterminacy.

The idea is particularly acute and the argument seemed unassailable. It's important to consider the impact of all of these exchanges on the people involved at the time. Leon Rosenfeld, a scientist who had participated in the Congress, described the event several years later:

> *It was a real shock for Bohr...who, at first, could not think of a solution. For the entire evening he was extremely agitated, and he continued passing from one scientist to another, seeking to persuade them that it could not be the case, that it would have been the end of physics if Einstein were right; but he couldn't come up with any way to resolve the paradox. I will never forget the image of the two antagonists as they left the club: Einstein, with his tall and commanding figure, who walked tranquilly, with a mildly ironic smile, and Bohr who trotted along beside him, full of excitement...The morning after saw the triumph of Bohr.*



George Gamow's make-believe experimental apparatus for validating the thought experiment at the Niels Bohr Institute in Copenhagen.

The "triumph of Bohr" consisted in his demonstrating, once again, that Einstein's subtle argument was not conclusive, but even more so in the way that he arrived at this conclusion by appealing precisely to one of the great ideas of Einstein: the principle of equivalence between gravitational mass and inertial mass. Bohr showed that, in order for Einstein's experiment to function, the box would have to be suspended on a spring in the middle of a gravitational field. In order to obtain a measurement of weight, a pointer would have to be attached to the box which corresponded with the index on a scale. After the release of a photon, weights could be added to the box to restore it to its original position and this would allow us to determine the weight. But in order to return the box to its original position, the box itself would have to be measured. The inevitable uncertainty of the position of the box translates into an uncertainty in the position of the pointer and of the determination of weight and therefore of energy. On the other hand, since the system is immersed in a gravitational potential which varies with the position, according to the principle of equivalence the uncertainty in the position of the clock implies an uncertainty with respect to its measurement of time and therefore of the value of the interval Δt . A precise evaluation of this effect leads to the conclusion that the relation $\Delta E \Delta t \geq h$ cannot be violated.

Post-Revolution: Second stage

The second phase of Einstein's "debate" with Bohr and the orthodox interpretation is characterized by an acceptance of the fact that it is, as a practical matter, impossible to simultaneously determine the values of certain incompatible quantities, but the rejection that this implies that these quantities do not actually have precise values. Einstein rejects the probabilistic interpretation of Born and insists that quantum probabilities are epistemic and not ontological in nature. As a consequence, the theory must be incomplete in some way. He recognizes the great value of the theory, but suggests that it "does not tell the whole story," and, while providing an appropriate description at a certain level, it gives no information on the more fundamental underlying level:

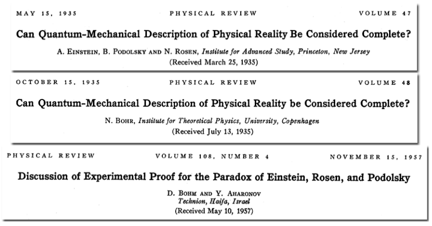
> *I have the greatest consideration for the goals which are pursued by the physicists of the latest generation which go under the name of quantum mechanics, and I believe that this theory represents a profound level of truth, but I also believe that the restriction to laws of a statistical nature will turn out to be transitory....Without doubt quantum mechanics has grasped an important fragment of the truth and will be a paragon for all future fundamental theories, for the fact that it must be deducible as a limiting case from such foundations, just as electrostatics is deducible from Maxwell's equations of the electromagnetic field or as thermodynamics is deducible from statistical mechanics.*

These thoughts of Einstein's would set off a line of research into hidden variable theories, such as the Bohm interpretation, in an attempt to complete the edifice of quantum theory. If quantum mechanics can be made *complete* in Einstein's sense, it cannot be done locally; this fact was demonstrated by John Stewart Bell with the formulation of Bell's inequality in 1964; however, should we live in a superdeterminist universe, that demonstration would not be valid, as admitted by Bell himself.

Post-Revolution: Third stage

The argument of EPR

In 1935 Einstein, Boris Podolsky and Nathan Rosen developed an argument, published in the magazine *Physical Review* with the title *Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?*, based on an entangled state of two systems. Before coming to this argument, it is necessary to formulate another hypothesis that comes out of Einstein's work in relativity: the principle of locality. *The elements of physical reality which are objectively possessed cannot be influenced instantaneously at a distance.*



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Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

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(Received March 25, 1935)

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Can Quantum-Mechanical Description of Physical Reality be Considered Complete?

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Discussion of Experimental Proof for the Paradox of Einstein, Rosen, and Podolsky

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Technion, Haifa, Israel
(Received May 10, 1957)

Title sections of historical papers on EPR.

The argument of EPR was in 1957 picked up by David Bohm and Yakir Aharonov in a paper published in *Physical Review* with the title *Discussion of Experimental Proof for the Paradox of Einstein, Rosen, and Podolsky.* The authors re-formulated the argument in terms of an entangled state of two particles, which can be summarized as follows:

1) Consider a system of two photons which at time *t* are located, respectively, in the spatially distant regions *A* and *B* and which are also in the entangled state of polarization $|\Psi\rangle$ described below:

$$|\Psi, t\rangle = 1/\sqrt{2}\,|1, V\rangle\,|2, V\rangle + 1/\sqrt{2}\,|1, H\rangle\,|2, H\rangle$$

2) At time *t* the photon in region A is tested for vertical polarization. Suppose that the result of the measurement is that the photon passes through the filter. According to the reduction of the wave packet, the result is that, at time *t+dt*, the system becomes:

$$|\Psi, t + dt\rangle = |1, V\rangle\,|2, V\rangle$$

3) At this point, the observer in A who carried out the first measurement on photon *1*, without doing anything else that could disturb the system or the other photon ("assumption (R)," below), can predict with certainty that photon *2* will pass a test of vertical polarization. It follows that photon *2* possesses an element of physical reality: that of having a vertical polarization.

4) According to the assumption of locality, it cannot have been the action carried out in A which created this element of reality for photon *2*. Therefore, we must conclude that the photon possessed the property of being able to pass the vertical polarization test *before* and *independently of* the measurement of photon *1*.

5) At time *t*, the observer in *A* could have decided to carry out a test of polarization at 45°, obtaining a certain result, for example, that the photon passes the test. In that case, he could have concluded that photon *2* turned out to be polarized at 45°. Alternatively, if the photon did not pass the test, he could have concluded that photon *2* turned out to be polarized at 135°. Combining one of these alternatives with the conclusion reached in 4, it seems that photon *2*, before the measurement took place, possessed both the property of being able to pass with certainty a test of vertical polarization and the property of being able to pass with certainty a test of polarization at either 45° or 135°. These properties are incompatible according to the formalism.

6) Since natural and obvious requirements have forced the conclusion that photon *2* simultaneously possesses incompatible properties, this means that, even if it is not possible to determine these properties simultaneously and

with arbitrary precision, they are nevertheless possessed objectively by the system. But quantum mechanics denies this possibility and it is therefore an incomplete theory.

Bohr's response

Bohr's response to this argument was published, five months later than the original publication of EPR, in the same magazine *Physical Review* and with exactly the same title as the original. The crucial point of Bohr's answer is distilled in a passage which he later had republished in Paul Arthur Schilpp's book *Albert Einstein, scientist-philosopher* in honor of the seventieth birthday of Einstein. Bohr attacks assumption (R) of EPR by stating:

> *The statement of the criterion in question is ambiguous with regard to the expression "without disturbing the system in any way". Naturally, in this case no mechanical disturbance of the system under examination can take place in the crucial stage of the process of measurement. But even in this stage there arises the essential problem of an influence on the precise conditions which define the possible types of prediction which regard the subsequent behaviour of the system...their arguments do not justify their conclusion that the quantum description turns out to be essentially incomplete...This description can be characterized as a rational use of the possibilities of an unambiguous interpretation of the process of measurement compatible with the finite and uncontrollable interaction between the object and the instrument of measurement in the context of quantum theory.*

John Bell later argued that this passage is almost unintelligible.[*citation needed*] What does Bohr mean, Bell asks, by the specification "mechanical" that is used to refer to the "disturbances" that Bohr maintains should not be taken into consideration? What is meant by the expression "an influence on the precise conditions" if not that different measurements in A provide different information on the system in B? This fact is not only admitted but is an essential part of the argument of EPR. Lastly, what could Bohr have meant by the expression 'uncontrollable interaction between the object and the measuring apparatus', considering that the central point of the argument of EPR is the hypothesis that, if one accepts locality, only the part of the system in A can be disturbed by the process of measurement and that, notwithstanding this fact, this process provides precise information on the part of the system in B? Is Bohr already contemplating the possibility of 'spooky action at a distance?' If so, why not declare it explicitly? If one abandons the assumption of locality, the argument of EPR obviously collapses immediately.

The debates represent one of the highest points of scientific research in the first half of the twentieth century because it called attention to an element of quantum theory, quantum non-locality, which is absolutely central to our modern understanding of the physical world.

Post-Revolution: Fourth stage

In his last writing on the topic[*citation needed*], Einstein further refined his position, making it completely clear that what really disturbed him about the quantum theory was the problem of the total renunciation of all minimal standards of realism, even at the microscopic level, that the acceptance of the completeness of the theory implied. Although the majority of experts in the field agree that Einstein was wrong, the current understanding is still not complete (see Interpretation of quantum mechanics). There is no scientific consensus that determinism would have been refuted.[5][6]

References

- Boniolo, G., (1997) *Filosofia della Fisica*, Mondadori, Milan.
- Bolles, Edmund Blair (2004) *Einstein Defiant*, Joseph Henry Press, Washington, D.C.
- Born, M. (1973) *The Born Einstein Letters*, Walker and Company, New York, 1971.
- Ghirardi, Giancarlo, (1997) *Un'Occhiata alle Carte di Dio*, Il Saggiatore, Milan.
- Pais, A., (1986) *Subtle is the Lord... The Science and Life of Albert Einstein*, Oxford University Press, Oxford, 1982.
- Shilpp, P.A., (1958) *Albert Einstein: Philosopher-Scientist*, Northwestern University and Southern Illinois University, Open Court, 1951.

[1] From Albert Einstein: Philosopher-Scientist (1949), publ. Cambridge University Press, 1949. Niels Bohr's report of conversations with Einstein.

[2] Pais

[3] Bolles

[4] . A reprint of this book was published by Edition Erbrich in 1982, ISBN 3-88682-005-X

Article Sources and Contributors

Albert Einstein *Source*: http://en.wikipedia.org/w/index.php?oldid=560027932 *Contributors*: (aeropagitica), -Paradox-, -jmac-, 01ianeo1, 100110100, 10FingerJoe, 1337u83r, 14Adrian, 152.163.195.xxx, 19chris95, 1exec1, 613kpiggy, 67688Q, 84user, 8thRSM, A Kit, A Man In Black, A Quest For Knowledge, A. B., A. di M., A.S. 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