This PDF file contains most of the text of the Web exhibit “Einstein – Image and Impact” at http://www.aip.org/history/einstein. NOT included are many secondary pages reached by clicking on the illustrations, which contain some additional information and photo credits. You must also visit the Web exhibit to explore hyperlinks within the exhibit and to other exhibits, and to hear voice clips, for which the text is supplied here.

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Formative Years I

Einstein's parents, Hermann and Pauline, middle-class Germans.
"I was the son of entirely irreligious (Jewish) parents," Einstein recalled.

"There was this huge world out there, independent of us human beings and standing before us like a great, eternal riddle, at least partly accessible to our inspection and thought. The contemplation of that world beckoned like a liberation."

The house where Einstein was born.

One story Einstein liked to tell about his childhood was of a "wonder" he saw when he was four or five years old: a magnetic compass. The needle's invariable northward swing, guided by an invisible force, profoundly impressed the child. The compass convinced him that there had to be "something behind things, something deeply hidden." Even as a small boy Einstein was self-sufficient and thoughtful. According to family legend he was a slow talker at first, pausing to consider what he would say. His sister remembered the concentration and perseverance with which he would build up houses of cards to many stories. The boy's thought was stimulated by his uncle, an engineer, and by a medical student who ate dinner once a week at the Einsteins'.

"At the age of 12, I experienced a wonder in a booklet dealing with Euclidean plane geometry, which came into my hands at the beginning of a school year. Here were assertions, as for example the intersection of the three altitudes of a triangle in one point, which -- though by no means evident -- could nevertheless be proved with such certainty that any doubt appeared to be out of the question. This lucidity and certainty made an indescribable impression on me."

School class photograph in Munich, 1889. Einstein is in the front row, second from right.

Although he got generally good grades (and was outstanding in mathematics), Einstein hated the academic high school he was sent to in Munich, where success depended on memorization and obedience to arbitrary authority. His real studies were done at home with books on mathematics, physics, and philosophy. A teacher suggested Einstein leave school, since his very presence destroyed the other students' respect for the teacher. The fifteen-year-old boy did quit school in mid-term to join his parents, who had moved to Italy.

Was Einstein's Brain Different?

Of course it was—people's brains are as different as their faces. In his lifetime many wondered if there was anything especially different in Einstein's. He insisted that on his death his brain be made available for research. When Einstein died in 1955, pathologist Thomas Harvey quickly preserved the brain and made samples and sections. He reported that he could see nothing unusual. The variations were within the range of normal human variations. There the matter rested until 1999. Inspecting samples that Harvey had carefully preserved, Sandra F. Witelson and colleagues discovered that Einstein's brain lacked a particular small wrinkle (the parietal operculum) that most people have. Perhaps in compensation, other regions on each side were a bit enlarged—the inferior parietal lobes. These regions are known to have something to do with visual imagery and mathematical thinking. Thus Einstein was apparently better equipped than most people for a certain type of thinking. Yet others of his day were probably at least as well equipped—Henri Poincar and David Hilbert, for example, were formidable visual and mathematical thinkers, both were on the trail of relativity, yet Einstein got far ahead of them. What he did with his brain depended on the nurturing of family and friends, a solid German and Swiss education, and his own bold personality.

A late bloomer: Even at the age of nine Einstein spoke hesitantly, and his parents feared that he was below average intelligence. Did he have a learning or personality disability (such as "Asperger's syndrome," a mild form of autism)? There is not enough historical evidence to say. Probably Albert was simply a thoughtful and somewhat shy child. If he had some difficulties in school, the problem was probably resistance to the authoritarian German teachers, perhaps compounded by the awkward situation of a Jewish boy in a Catholic school.

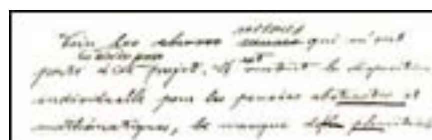
Formative Years II

"It is almost a miracle that modern teaching methods have not yet entirely strangled the holy curiosity of inquiry; for what this delicate little plant needs more than anything, besides stimulation, is freedom."

Einstein with his sister.

Einstein's family had moved to Italy to try to establish a business, and he joined them for a glorious half year of freedom from work and anxiety. In 1895 he took the entrance examination for the Swiss Federal Institute of Technology -- and he failed. He was advised to study at a Swiss school in Aarau; here his teachers were humane and his ideas were set free. His thoughts turned to the theory of electromagnetism formulated by James Clerk Maxwell, seldom taught even in universities at the turn of the century.

From a classroom essay Einstein wrote in French at the age of 16, explaining why he would like to study theoretical mathematics or physics: "Above all it is my individual disposition for abstract and mathematical thought, my lack of imagination and practical talent. My inclinations have also led me to this resolve. That is quite natural; one always likes to do things for which one has talent. And then there is a certain independence in the scientific profession which greatly pleases me."



The Swiss Federal Institute of Technology ("ETH"), Zurich.

Einstein graduated from the Aarau school and entered the Institute of Technology in Zurich. Around this time he recognized that physics was his true subject. Only there could he "seek out the paths that led to the depths." He also realized that he could never be an outstanding student. Fortunately his friend Marcel Grossmann had the conventional traits Einstein lacked. While Einstein worked in the library or the laboratory, Grossmann took excellent notes at the mathematics lectures, and gladly shared them with his friend before examinations. Einstein later wrote, "I would rather not speculate on what would have become of me without these notes."

Einstein with his friend Marcel Grossman (left).

Einstein grew familiar with the successes of past scientists who had tried to explain the world entirely through atoms or fluids, interacting like parts of a machine. But he learned that Maxwell's theory of electricity and magnetism was defying efforts to reduce it to mechanical processes. Through a new friend, the engineer Michele Besso, Einstein came to the writings of Ernst Mach -- a skeptical critic of accepted ideas in physics.

Formative Years III

"As a somewhat precocious young man, I was struck by the futility of the hopes and the endeavors that most men chase restlessly throughout life. And I soon realized the cruelty of that chase, which in those days was more carefully disguised with hypocrisy and glittering words than it is today."

The patent office in Bern.

After Einstein graduated with an undistinguished record, he made a number of efforts to get a university job, and failed. He found only occasional jobs on the periphery of the academic world. He felt he was a burden on his none too prosperous family, and wondered if he had been mistaken in trying to become a physicist. Finally he got a position at the Swiss Patent Office in Bern. It was "a kind of salvation," he said. The regular salary and the stimulating work evaluating patent claims freed Einstein. He now had time to devote his thought to the most basic problems of physics of his time, and began to publish scientific papers.

Michele Besso

"Academy" members Konrad Habricht, Maurice Solovine, and Einstein.

Einstein's closest friend, with whom he walked home from the Patent Office every day, was Michele Besso. Einstein thought him "the best sounding board in Europe" for scientific ideas. With other friends in Bern, all unknown to the academic world, Einstein met regularly to read and discuss books on science and philosophy. They called themselves the Olympia Academy, mocking the official bodies that dominated science.

Einstein's began to attract respect with his published papers (described in the next section), and in 1909 he was appointed associate professor at the University of Zurich. He was also invited to present his theories before the annual convention of German scientists. He met many people he had known only through their writings, such as the physicist Max Planck of Berlin. Soon Einstein was invited to the German University in Prague as full professor. Here he met a visiting Austrian physicist, Paul Ehrenfest. "Within a few hours we were true friends," Einstein recalled, "as though our dreams and aspirations were made for each other."

Formative Years IV

Einstein, his wife Mileva, and their son.

At the Zurich Polytechnic a romance had arisen between the handsome and witty would-be science teacher and a young Serbian woman, Mileva Maric, the only woman in Albert's physics class. Einstein's family opposed any talk of marriage, even after Mileva gave birth to a daughter (who was apparently given up for adoption). The pair finally married in 1903 after Einstein got his job at the Patent Office. Einstein discussed physics with Mileva, but there is no solid evidence that she made any significant contribution to his work. In 1904 a son was born, and a second in 1910.

Einstein in 1912

Through letters, visits, and science meetings, Einstein came to know most of the major physicists of Europe (there were not many in those days). In 1912 Einstein was invited back to the Swiss Federal Institute of Technology as professor. Here he rejoined his old friend Marcel Grossmann, now professor of mathematics. With Grossmann's aid, Einstein studied the mathematical theories and techniques which he found necessary for his work toward a new theory of gravitation. Meanwhile, Einstein was being introduced to a different sort of world by another friend, Friedrich Adler: the world of the Second International and its attempt to halt the growth of international rivalries in Europe.

In 1914, the German government gave Einstein a senior research appointment in Berlin, along with a membership in the prestigious Prussian Academy of Sciences. When Einstein had left his native land as a youth, he had renounced German citizenship and all of the militarist German society. But Berlin -- with no teaching duties and a galaxy of top scientists for colleagues -- could not be resisted. It was the highest level a scientific career could ordinarily reach.

"With such fame, not much time remains for his wife," Mileva complained. "I am very starved for love." Einstein felt suffocated in the increasingly strained and gloomy relationship. He found solace in a love affair with his cousin, Elsa Löwenthal. Mileva and Albert separated in 1914, after bitter arguments, and divorced in 1919. That same year he married Elsa, and settled in with her and her two grown daughters by a previous marriage. "The Lord has put into him so much that's beautiful, and I find him wonderful," Elsa later wrote, "even though life at his side is enervating and difficult." (Click here for more on Einstein at home.)

The Great Works I

"A storm broke loose in my mind."

March 1905

Einstein sent to the *Annalen der Physik*, the leading German physics journal, a paper with a new understanding of the structure of light. He argued that light can act as though it consists of discrete, independent particles of energy, in some ways like the particles of a gas. A few years before, Max Planck's work had contained the first suggestion of a discreteness in energy, but Einstein went far beyond this. His revolutionary proposal seemed to contradict the universally accepted theory that light consists of smoothly oscillating electromagnetic waves. But Einstein showed that light quanta, as he called the particles of energy, could help to explain phenomena being studied by experimental physicists. For example, he made clear how light ejects electrons from metals.

Einstein *in the patent office*.

Einstein discovered light quanta by pondering experiments on particles discovered only a few years earlier. See our Web exhibit, The Discovery of the Electron.

May 1905

The *Annalen der Physik* received another paper from Einstein. The well-known kinetic energy theory explained heat as an effect of the ceaseless agitated motion of atoms; Einstein proposed a way to put the theory to a new and crucial experimental test. If tiny but visible particles were suspended in a liquid, he said, the irregular bombardment by the liquid's invisible atoms should cause the suspended particles to carry out a random jittering dance. Just such a random dance of microscopic particles had long since been observed by biologists (It was called "Brownian motion," an unsolved mystery). Now Einstein had explained the motion in detail. He had reinforced the kinetic theory, and he had created a powerful new tool for studying the movement of atoms.

"When the Special Theory of Relativity began to germinate in me, I was visited by all sorts of nervous conflicts... I used to go away for weeks in a state of confusion."

June 1905

Einstein sent the *Annalen der Physik* a paper on electromagnetism and motion. Since the time of Galileo and Newton, physicists had known that laboratory measurements of mechanical processes could never show any difference between an apparatus at rest and an apparatus moving at constant speed in a straight line. Objects behave the same way on a uniformly moving ship as on a ship at the dock; this is called the Principle of Relativity. But according to the electromagnetic theory, developed by Maxwell and refined by Lorentz, light should not obey this principle. Their electromagnetic theory predicted that measurements on the velocity of light would show the effects of motion. Yet no such effect had been detected in any of the ingenious and delicate experiments that physicists had devised: the velocity of light did not vary.

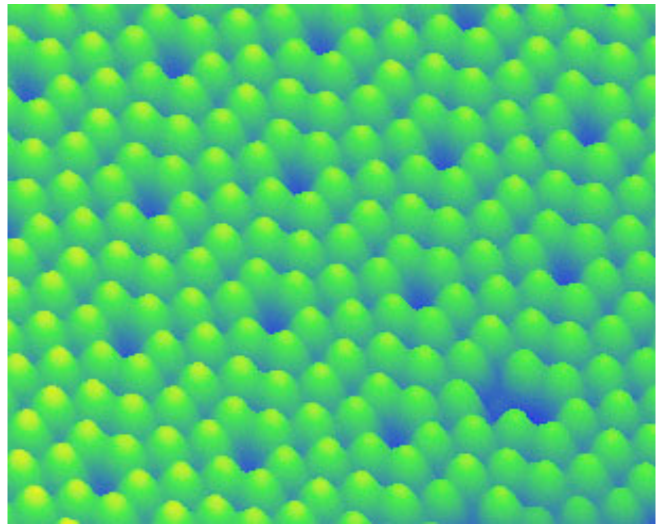
Time and motion: the old clock tower and an electrified trolley in Bern.

Einstein had long been convinced that the Principle of Relativity must apply to all phenomena, mechanical or not. Now he found a way to show that this principle was compatible with electromagnetic theory after all. As Einstein later remarked, reconciling these seemingly incompatible ideas required "only" a new and more careful consideration of the concept of time. His new theory, later called the special theory of relativity, was based on a novel analysis of space and time -- an analysis so clear and revealing that it can be understood by beginning science students.

September 1905

Einstein reported a remarkable consequence of his special theory of relativity: if a body emits a certain amount of energy, then the mass of that body must decrease by a proportionate amount. Meanwhile he wrote a friend, "The relativity principle in connection with the Maxwell equations demands that the mass is a direct measure for the energy contained in bodies; light transfers mass... This thought is amusing and infectious, but I cannot possibly know whether the good Lord does not laugh at it and has led me up the garden path." Einstein and many others were soon convinced of its truth. The relationship is expressed as an equation: $E=mc^2$.

Atoms in a Crystal...

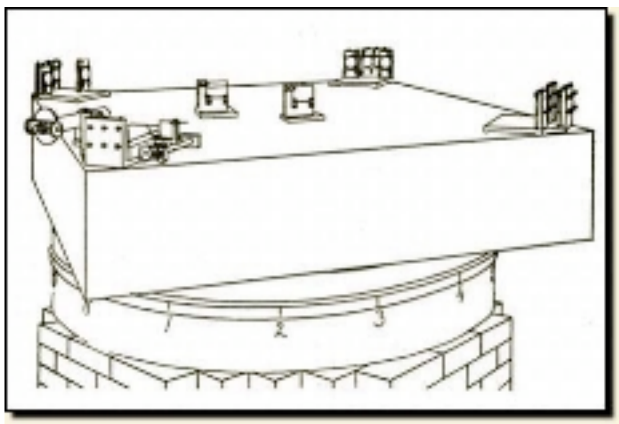


This is an image of silicon atoms arranged on a face of a crystal. It is impossible to "see" atoms this way using ordinary light. The image was made by a Scanning Tunneling Microscope, a device that "feels" the cloud of electrons that form the outer surface of atoms, rather as a phonograph needle feels the grooves in a record.

It had long been suspected that crystals are made of atoms lined up in neat arrays. But at the start of the 20th century there was no way to actually see them. Some scientists thought the "atom" in physics theories might be merely a sort of abstract device useful for computations. Einstein's paper gave one of the first convincing proofs that atoms do exist as real objects.

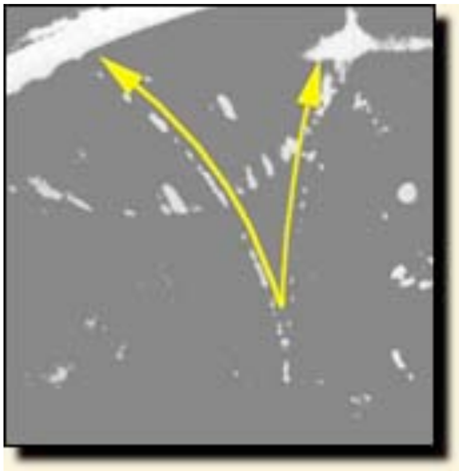
$E = mc^2$

"In light of knowledge attained, the happy achievement seems almost a matter of course, and any intelligent student can grasp it without too much trouble. But the years of anxious searching in the dark, with their intense longing, their alterations of confidence and exhaustion and the final emergence into the light -- only those who have experienced it can understand it."



Einstein's theories sprang from a ground of ideas prepared by decades of experiments. One of the most striking, in retrospect, was done in Cleveland, Ohio, by Albert Michelson and Edward Morley in 1887. Their apparatus, shown above, was a massive stone block with mirrors and crisscrossing light beams, giving an accurate measurement of any change in the velocity of light. Michelson and Morley expected to see their light beams shifted by the swift motion of the earth in space. To their surprise, they could not detect any change. It is debatable whether Einstein paid heed to this particular experiment, but his work provided an explanation of the unexpected result through a new analysis of space and time.

As noted on the previous page, when Einstein used his equations to study the motion of a body, they pointed him to a startling insight about the body's mass and energy.



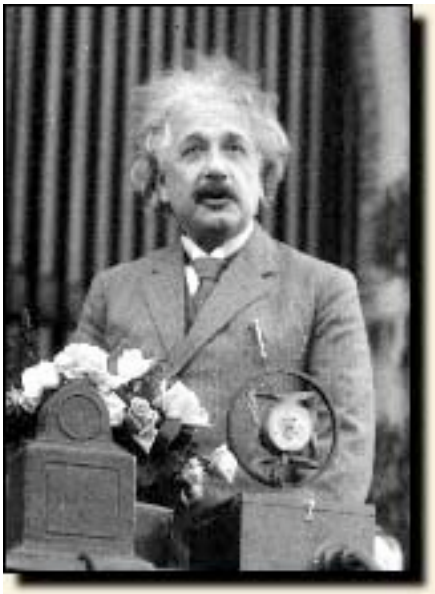
Conversion of energy into mass

The deep connection Einstein discovered between energy and mass is expressed in the equation $E=mc^2$. Here E represents energy, m represents mass, and c^2 is a very large number, the square of the speed of light. Full confirmation was slow in coming. In Paris in 1933, Irène and Frédéric Joliot-Curie took a photograph showing the conversion of energy into mass. A quantum of light, invisible here, carries energy up from beneath. In the middle it changes into mass -- two freshly created particles which curve away from each other.

Meanwhile in Cambridge, England, the reverse process was seen: the conversion of mass into pure energy. With their apparatus John Cockcroft and E.T.S. Walton broke apart an atom. The fragments had slightly less mass in total than the original atom, but they flew apart with great energy.

$$E = mc^2$$

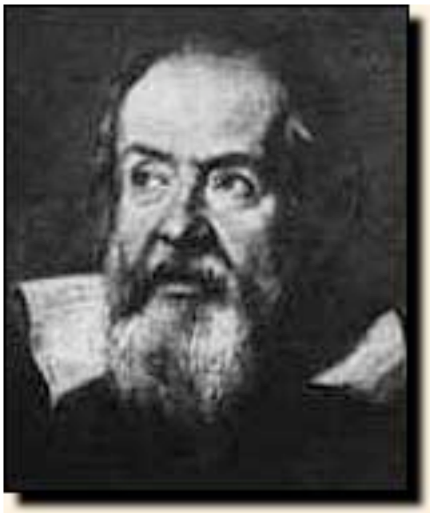
Einstein Explains the Equivalence of Energy and Matter



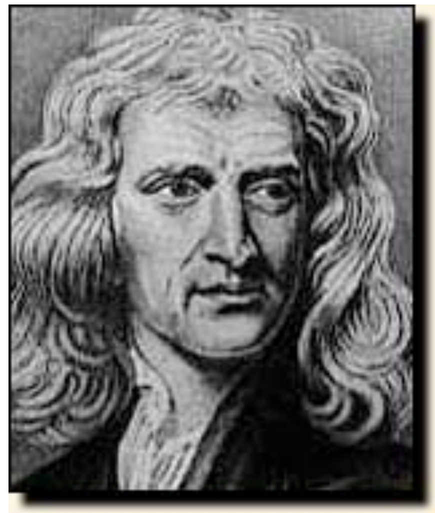
"It followed from the special theory of relativity that mass and energy are both but different manifestations of the same thing -- a somewhat unfamiliar conception for the average mind. Furthermore, the equation E is equal to m c-squared, in which energy is put equal to mass, multiplied by the square of the velocity of light, showed that very small amounts of mass may be converted into a very large amount of energy and vice versa. The mass and energy were in fact equivalent, according to the formula mentioned before. This was demonstrated by Cockcroft and Walton in 1932, experimentally."

The Great Works II

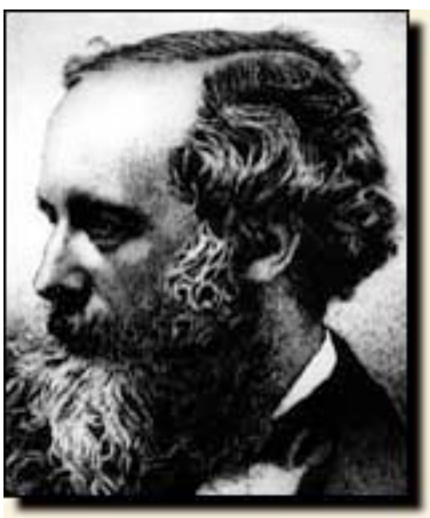
"The four men who laid the foundations of physics on which I have been able to construct my theory... "



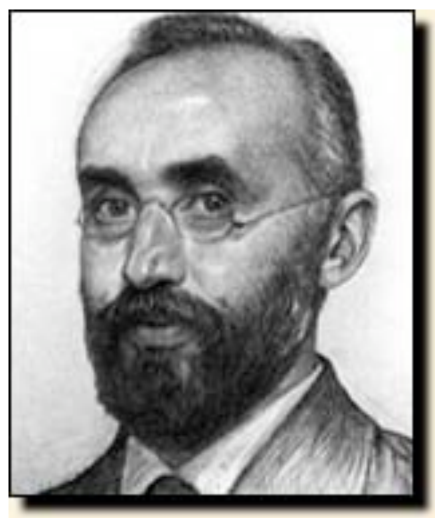
Galileo



Isaac Newton



James Clerk Maxwell



Hendrik Antoon Lorentz

1907-1915

As early as 1907, while Einstein and others explored the implications of his special theory of relativity, he was already thinking about a more general theory. The special theory had shown how to relate the measurements made in one laboratory to the measurements made in another laboratory moving in a uniform way with respect to the first laboratory. Could he extend the theory to deal with laboratories moving in arbitrary ways, speeding up, slowing down, changing direction? Einstein saw a possible link between such accelerated motion and the familiar force of gravity. He was impressed by a fact known to Galileo and Newton but not fully appreciated before Einstein puzzled over it. All bodies, however different, if released from the same height will fall with exactly the same constant acceleration (in the absence of air resistance). Like the invariant velocity of light on which Einstein had founded his special theory of relativity, here was an invariance that could be the starting point for a theory.

"The physicist cannot simply surrender to the philosopher the critical contemplation of the theoretical foundations; for he himself knows best and feels most surely where the shoe pinches.... he must try to make clear in his own mind just how far the concepts which he uses are justified... The whole of science is nothing more than a refinement of everyday thinking."

As he often did in his work, Einstein used a "thought experiment." Suppose that a scientist is enclosed in a large box somewhere, and that he releases a stone. The scientist sees the stone fall to the floor of the box with a constant acceleration. He might conclude that his box is in a place where there is a force of gravity pulling downward. But this might not be true. The entire box could be free from gravity, but accelerating upward in empty space on a rocket: the stone could be stationary and the floor rising to meet it. The physicist in the box cannot, Einstein noted, tell the difference between the two cases. Therefore there must be some profound connection between accelerated motion and the force of gravity. It remained to work out this connection.

Einstein began to search for particular equations -- ones that would relate the measurements made by two observers who are moving in an arbitrary way with respect to one another. The search was arduous, with entire years spent in blind alleys. Einstein had to master more elaborate mathematical techniques than he had ever expected to need, and to work at a higher level of abstraction than ever before. His friend Michele Besso gave crucial help here. Meanwhile his life was unsettled. He separated from his wife. And he began to participate in politics after the First World War broke out.

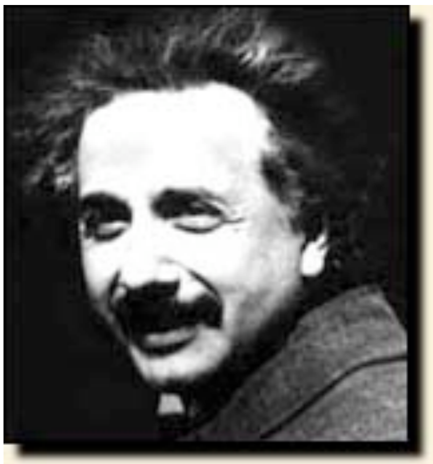
"I have just completed the most splendid work of my life..."

--to his son Hans Albert, 1915

Success in his theoretical work was sealed in 1915. The new equations of gravitation had an essential logical simplicity, despite their unfamiliar mathematical form. To describe the action of gravity, the equations showed how the presence of matter warped the very framework of space and time. This warping would determine how an object moved. Einstein tested his theory by correctly calculating a small discrepancy in the motion of the planet Mercury, a discrepancy that astronomers had long been at a loss to explain.

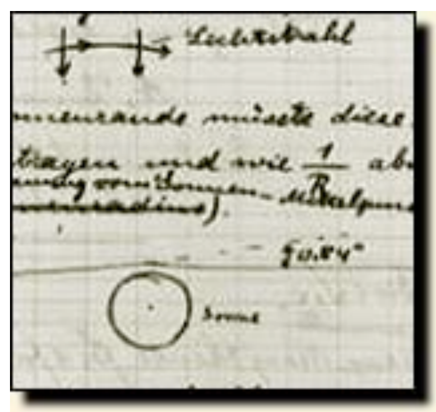
World Fame I

"Dear Mother, -- Good news today. H.A. Lorentz has wired me that the British expeditions have actually proved the light deflection near the sun."

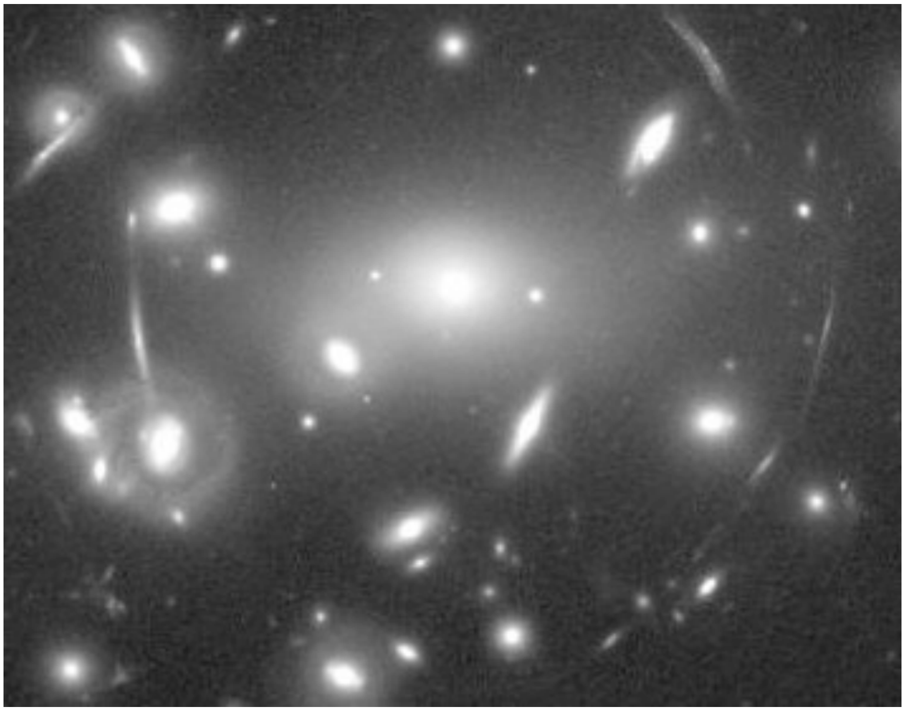


Einstein's new general theory of relativity predicted a remarkable effect: when a ray of light passes near a massive body, the ray should be bent. For example, starlight passing near the sun should be slightly deflected by gravity. This deflection could be measured when the sun's own light was blocked during an eclipse. Einstein predicted a specific amount of deflection, and the prediction spurred British astronomers to try to observe a total eclipse in May 1919. Feverish preparations began as the war ended. Two expeditions, one to an island off West Africa and the other to Brazil, succeeded in photographing stars near the eclipsed sun. The starlight had been deflected just as Einstein had predicted.

In a letter to an astronomer in 1913, Einstein included a sketch (right) that showed how gravity should deflect light near the sun, making stars appear to shift their positions. A photograph (below) from one of the expeditions shows the eclipsed sun. Some stars are circled and artificially enhanced in this reproduction. These apparent positions deviated from the positions of the stars photographed when the sun was elsewhere in the sky. As a ripple a pane of in glass is detected when objects seen through the glass are distorted, so we detect here a warping of space itself.



A Gravitational Lens...



This photo taken with the Hubble Space Telescope shows a cluster of galaxies. Each of the bright rounded objects contains billions of stars. The huge concentrated mass of the cluster warps space around it, bending the light that comes through from galaxies lying far beyond the cluster. Each of the streaks and arcs in the photo is a smeared-out image of one of those distant galaxies.

Measuring the streaks and applying Einstein's equations, physicists can calculate the distribution of matter in this cluster of galaxies. Astronomers are also using the cluster itself as a sort of telescope. This powerful "gravitational lens" gathers light from galaxies so remote that we could not see them by other means. Some of the light you see here originated when the universe was barely a quarter of its present age.

World Fame II

"Since that deluge of newspaper articles I have been so flooded with questions, invitations, suggestions, that I keep dreaming I am roasting in Hell, and the mailman is the devil eternally yelling at me, showering me with more bundles of letters at my head because I have not answered the old ones."

Announcement of the eclipse results caused a sensation, and not only among scientists. It brought home to the public a transformation of physics, by Einstein and others, that was overturning established views of time, space, matter, and energy. Einstein became the world's symbol of the new physics. Some journalists took a perverse delight in exaggerating the incomprehensibility of his theory, claiming that only a genius could understand it. More serious thinkers -- philosophers, artists, ordinary educated and curious people -- took the trouble to study the new concepts. These people too chose Einstein as a symbol for thought at its highest.

Cartoon

"I have become rather like King Midas, except that everything turns not into gold but into a circus."

With his second wife, Elsa, Einstein toured the US in 1921 like a celebrity. His name and face became familiar even in cartoons and advertisements.

Public Concerns I

"The state exists for man, not man for the state. The same may be said of science. These are old phrases, coined by people who saw in human individuality the highest human value. I would hesitate to repeat them, were it not for the ever recurring danger that they may be forgotten, especially in these days of organization and stereotypes."

The outbreak of the First World War brought Einstein's pacifist sympathies into public view. Ninety-three leading German intellectuals, including physicists such as Planck, signed a manifesto defending Germany's war conduct. Einstein and three others signed an antiwar counter-manifesto. He helped to form a nonpartisan coalition that fought for a just peace and for a supranational organization to prevent future wars. As a Swiss citizen Einstein could feel free to spend his time on theoretical physics, but he kept looking for ways to reconcile the opposing sides. "My pacifism is an instinctive feeling," he said, "a feeling that possesses me because the murder of men is disgusting. My attitude is not derived from any intellectual theory but is based on my deepest antipathy to every kind of cruelty and hatred."

Along with Germany's military collapse in November 1918, chaotic workers' and soldiers' councils proliferated. One of Einstein's lectures at the University of Berlin was "canceled due to revolution." On November 16 Einstein was one of the original signers of a manifesto announcing the creation of a progressive middle-class party, the German Democratic Party. After a democratically elected assembly met in Weimar, Einstein formally accepted German citizenship as a gesture of support for the infant republic.

The 1920 Kapp Putsch, an attempted coup by monarchists, was only one of many disturbances in Berlin.

Einstein in Berlin with political figures.

With his scientific fame Einstein could act as unofficial spokesman for the Weimar Republic, and he protested the continued hostility of Germany's former enemies. In 1921 he refused to attend the third Solvay Congress in Belgium, since all other German scientists were excluded from it. In 1922 he joined a newly created Committee on Intellectual Cooperation set up under the League of Nations. The next year he resigned, distressed by the League's impotence when confronted with France's occupation of the German Ruhr. But he soon returned to the committee. As a leading member of the German League for Human Rights, he worked hard for better relations with France. He also made numerous gestures against militarism.

Einstein attracted attention to a number of causes, such as the release of political prisoners and the defense of democracy against the spread of fascism. He spoke in public, made statements to the press, signed petitions. In 1924 he defended the radical Bauhaus School of Architecture; in 1927 he signed a protest against Italian fascism; in 1929 he appealed for the commutation of death sentences given to Arab rioters in British Palestine.

While not a practicing Jew, Einstein took opportunities to show support for the German Jewish community when it was attacked by anti-Semites.

Public Concerns II

Einstein visiting the Physics Institute in Leiden, The Netherlands.

Einstein traveled widely in the 1920s, both as a spokesman for liberal causes and as an esteemed member of the physics community. He visited England, France, Austria, Czechoslovakia, and South America and traveled east as far as Japan, returning by way of Palestine and Spain. In 1922 he went to Sweden to accept a Nobel Prize in physics. Between 1930 and 1933 he spent each winter in Pasadena at the California Institute of Technology, each spring in Berlin, and each summer near Berlin in a home at Caputh.

"How I wish that somewhere there existed an island for those who are wise and of goodwill! In such a place even I would be an ardent patriot."

The "Einstein Tower" in Germany.

An anti-Semitic cartoon from 1932.

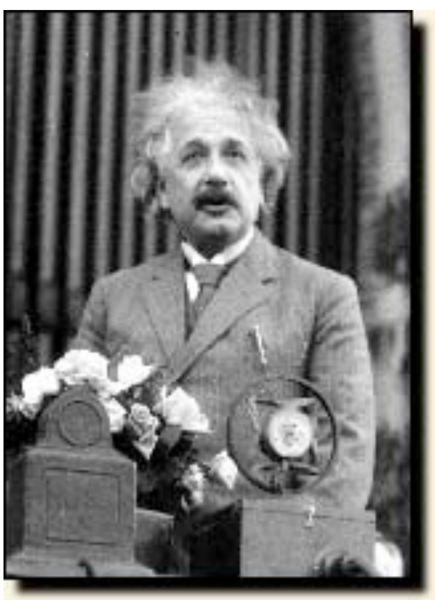
Anti-Semitism was openly pursued by the powerful political right and the emerging Nazi party since 1919. Nazi physicists and their followers violently denounced Einstein's theory of relativity as "Jewish-Communist physics." At times his friends feared for his safety. Such anti-Semitism was one reason why Einstein, although he believed in world government rather than nationalism, gave public support to Zionism. "In so far as a particular community is attacked as such," he said, "it is bound to defend itself as such, so that its individual members may be able to maintain their material and spiritual interests... In present circumstances the rebuilding of Palestine is the only object that has a sufficiently strong appeal to stimulate the Jews to effective corporate action." But he objected to a law that required him to join the official Jewish religious community in Berlin. He said, "Much as I feel myself a Jew, I feel far removed from traditional religious forms."

As the Nazi movement grew stronger, Einstein helped to organize a non-partisan group, within the Jewish community, that advocated a united stand against fascism. Hitler's climb to power, bringing official support of vicious anti-Semitism, was making the position of Jews and other opponents of Nazism impossible. After Einstein left Germany in 1932 he never returned. In March 1933 he once again renounced German citizenship. His remaining property in Germany was confiscated, and his name appeared on the first Nazi list of people stripped of their citizenship.

Einstein just before he left his homeland

Many universities abroad were eager to invite the renowned scientist, but he had already accepted an offer to join the Institute for Advanced Study in Princeton, New Jersey. He arrived in the United States in October 1933, and in 1940 became an American citizen. In 1936 his wife Elsa died. One of her daughters and Einstein's long-time secretary lived on with Einstein in Princeton and helped with housekeeping.

Einstein Speaks on the Fate of the European Jews…



"As long as Nazi violence was unleashed only, or mainly, against the Jews, the rest of the world looked on passively and even treaties and agreements were made with the patently criminal government of the Third Reich.... The doors of Palestine were closed to Jewish immigrants, and no country could be found that would admit those forsaken people. They were left to perish like their brothers and sisters in the occupied countries. We shall never forget the heroic efforts of the small countries, of the Scandinavian, the Dutch, the Swiss nations, and of individuals in the occupied part of Europe who did all in their power to protect Jewish lives."

Public Concerns III

[In London](#), 1933.

During a stay in England in September 1933, Einstein met with Winston Churchill, Lloyd George, and prominent British scientists and intellectuals. He tried to warn them of the Nazi danger. Many noted academics were fleeing Germany, few of them received abroad as warmly as Einstein. He worked on behalf of the Emergency Committee to Aid Displaced German Scholars and other organizations that tried to find homes for both Jewish and political refugees.

A Sample of Einstein's Public Activities: 1930-1935

1930

- With Stefan Zweig, Bertrand Russell, and others, signs petition favoring the Kellogg-Briand arms limitation pact.
- Appeals against conscription and military training of young men; signs petition with Thomas Mann, Romain Rolland, and others.
- Speaks at the New History Society, New York, translated by the pacifist Rosika Schwimmer.

1931

- Attends special screening in Hollywood of "All Quiet on the Western Front," a film banned in Germany; supports the German League for Human Rights campaign to have the film shown in Germany.
- Speaks at the California Institute of Technology on the social role of science.
- Addresses a peace group at Chicago railway station.
- Joins an international protest to save lives of eight Scottsboro, Alabama blacks wrongly convicted of rape.
- Speaks at a mass protest meeting supporting E.J. Grumbel, a liberal professor under attack in Germany.
- Supports the International Union of Anti-militarist Clergymen and Ministers, who call for a Geneva peace conference.
- Speaks at a student meeting of League of The Nations Association.
- Meets with War Resisters International; sends message to their conference in France.

1932

- Attends meeting of the Los Angeles University of International Relations.
- Speaks to the Joint Peace Council, with Lord Ponsonby, on the failure of disarmament conferences.
- Exchanges letters with Freud under auspices of International Institute of Intellectual Cooperation, leading to publication of pamphlet, "Why War?"

1933

- Addresses student group at the California Institute of Technology in Pasadena.
- Resigns from the Prussian and Bavarian Academies of Science in protest after Hitler takes power; in open letter, he denies the accusation that he spread propaganda on anti-Semitic atrocities.
- Accepts election as a Founding Member, with Lord Davies, of the New Commonwealth Society; discusses international army and navy police force.
- Speaks at a mass meeting in London for the Refugee Assistance Fund to aid victims of the Nazis.
- Guest of honor at the World Peaceways dinner in New York.

1934

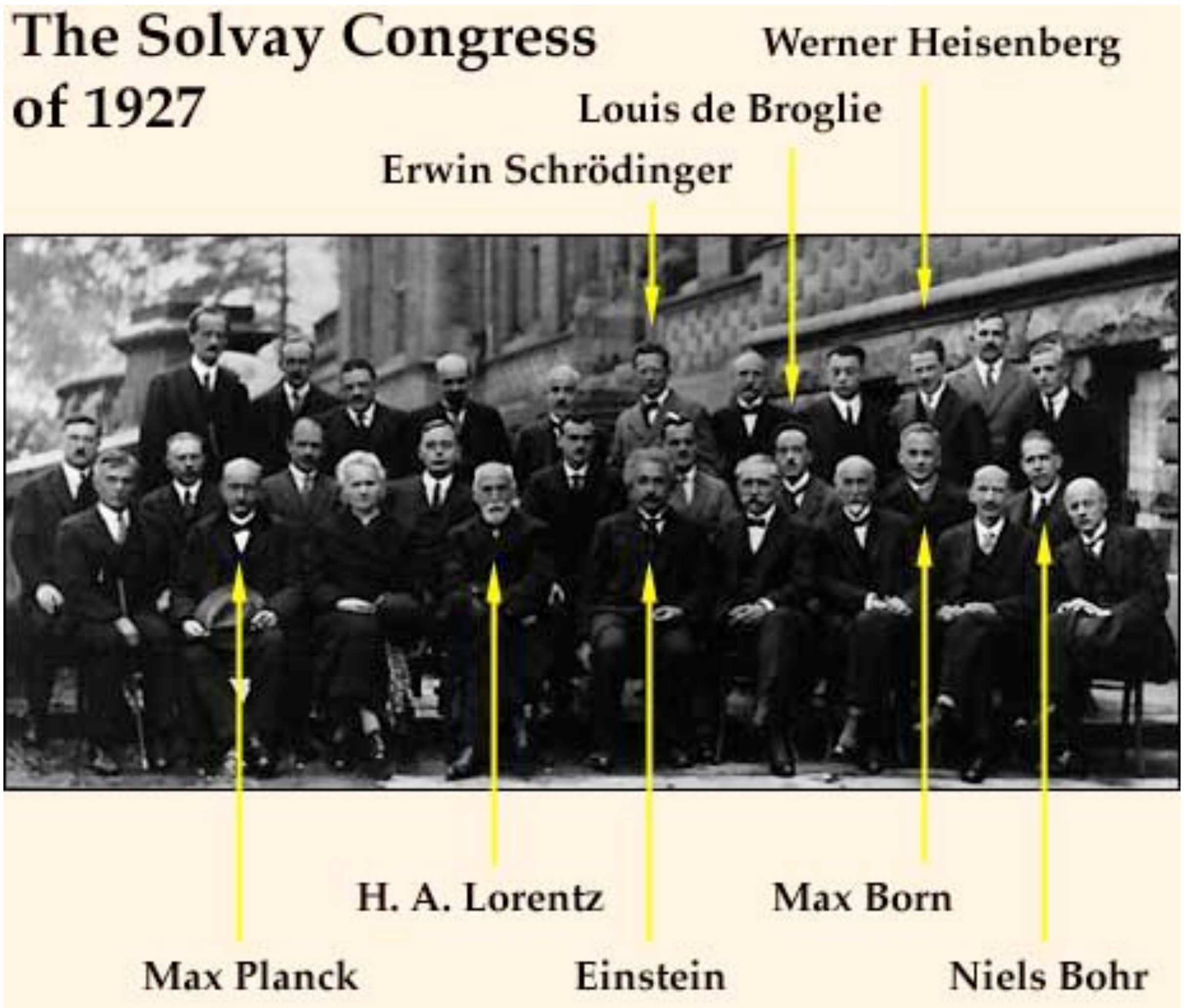
- Speaks at a Princeton, New Jersey state conference on Causes and Cures of War.
- Sends letter to the Anti-War Committee at New York University.
- Makes national radio speech on Brotherhood Day, sponsored by National Conference of Christians and Jews.
- Sends message to the Educators and World Peace conference of the Progressive Education Association in New York.

1935

- With Alfred E. Smith, speaks on national radio and at a New York dinner to aid political and non-Jewish refugees from Germany.
- Helps to initiate campaign for a Nobel Peace Prize for the pacifist Carl von Ossietzky, then ill in a German concentration camp.
- With John Dewey and Alvin Johnson, becomes member of the United States section of the International League for Academic Freedom.
- Speaks at Passover celebration in at the Manhattan Opera House, urging Jewish-Arab amity in Palestine.

The Quantum and the Cosmos I

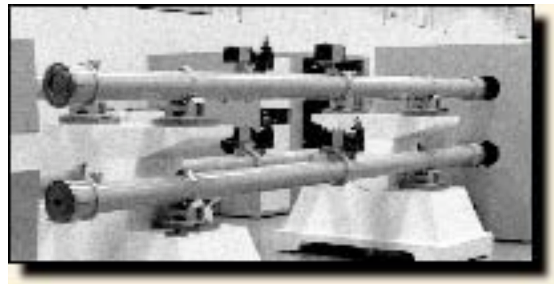
"Of all the communities available to us there is not one I would want to devote myself to, except for the society of the true searchers, which has very few living members at any time."



- **Max Planck** found the first hints of the quantum theory in 1900.
- **H.A. Lorentz**: "He meant more than all the others I have met on life's journey."
- **Erwin Schrödinger** and **Louis de Broglie** developed a quantum theory that appealed to Einstein. He said de Broglie had "lifted a corner of the great veil." But it was soon found that this theory was mathematically equivalent to the Heisenberg theory, which Einstein distrusted.
- **Max Born**, another pioneer of the quantum theory, was a friend of Einstein for many years.

In 1916 Einstein devised an improved fundamental statistical theory of heat, embracing the quantum of energy. His theory predicted that as light passed through a substance it could stimulate the emission of more light. This effect is at the heart of the modern laser.

This theory was further developed by the Indian physicist S.N. Bose. He sent a draft paper to Einstein, who was inspired to develop a still more general approach. The terms stimulation and cooperative phenomena, used in laser physics, could describe the discovery process as well.



*LASER: **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.*

The Danish physicist Niels Bohr showed in 1913 how the quantum idea could explain the actions of electrons inside atoms.

By the 1920s most physicists had realized that their familiar mechanics, developed over centuries by Newton and many others, could not fully describe the world of atoms. Physics had to be rebuilt to take into account the fundamental discreteness of energy that was first pointed out by Planck and Einstein. Einstein himself contributed a number of key ideas to the developing quantum theory. But through the early 1920s much in quantum theory remained obscure.

Beginning in 1925 a bold new quantum theory emerged, the creation of a whole generation of theoretical physicists from many nations. Soon scientists were vigorously debating how to interpret the new quantum mechanics. Einstein took an active part in these discussions. Heisenberg, Bohr, and other creators of the theory insisted that it left no meaningful way open to discuss certain details of an atom's behavior. For example, one could never predict the precise moment when an atom would emit a quantum of light. Einstein could not accept this lack of certainty; and he raised one objection after another. At the Solvay Conferences of 1927 and 1930 the debate between Bohr and Einstein went on day and night, neither man conceding defeat.

The German physicist Werner Heisenberg. His 1925 quantum equations opened the way to a complete description of atomic mechanics. **See our big online exhibit Werner Heisenberg and the Uncertainty Principle.**

"Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing. The theory says a lot, but does not really bring us closer to the secret of the 'Old One.' I, at any rate, am convinced that He is not playing at dice."

Einstein and Bohr

By the mid 1930s, Einstein had accepted quantum mechanics as a consistent theory for the statistics of the behavior of atoms. He recognized that it was "the most successful physical theory of our time." This theory, which he had helped to create, could explain nearly all the physical phenomena of the everyday world. Eventually the applications would include transistors, lasers, a new chemistry, and more. Yet Einstein could not accept quantum mechanics as a completed theory, for its mathematics did not describe individual events. Einstein felt that a more basic theory, one that could completely describe how each individual atom behaved, might yet be found. By following the approach of his own general theory of relativity, he hoped to dig deeper than quantum mechanics. The search for a deeper theory was to occupy much of the rest of his life.

You're Looking at Quanta...

Streams of electrons shoot at your monitor's screen from behind, and where an electron hits, it kicks out a packet of light energy. Energy is exchanged in fixed discrete quantities, Einstein's "quanta." So a particular screen material, hit by an electron, releases a light packet with a specific amount of energy.

In the retina of your eye there are molecules in which the links between atoms are under tension, like tiny mousetraps that can be set off by a specific energy. (Different energies will appear to you as different colors, red or blue or green.) When a light packet of the right energy strikes a molecule of the right type, it may trigger the molecule to straighten out. This snap launches reactions that send a signal up a nerve to your brain.

But the molecule is not always triggered. Sometimes the light just goes on through, without transferring its quantum of energy. Bohr held that it is a matter of pure chance whether the interaction will happen in any particular case. What can be calculated is the *probability* that the energy will be exchanged--say, seven out of ten times that a light packet meets a molecule of a given type. If your eyes were more sensitive, at very low levels of light you would see, instead of a constant image, a sparkling, "grainy" picture made up of random flashes.

Is nature truly random at its foundations? Recent experiments at extremely low light levels have found examples of the strange behavior that Bohr's interpretation predicts. Einstein lost the debate... But Bohr has not won it. Physicists today continue to debate how to explain the intractably weird laws of quanta.

The Quantum and the Cosmos II

"I believe in Spinoza's God who reveals himself in the orderly harmony of what exists, not in a God who concerns himself with the fates and actions of human beings."

galaxy

The general theory of relativity, unlike quantum theory, was not rapidly developed after Einstein showed the way. Gravity was now understood in a new way, but the equations were difficult to work with. And the characteristics of the theory showed up clearly only under extreme conditions, enormous densities or vast spaces or measurements of the highest precision. Eventually technology caught up -- the modern Global Positioning System cannot pin down a location without using the equations of general relativity to adjust for effects of gravity and speed. And astronomers have discovered black holes, objects with so much mass that they cannot be understood at all without Einstein's equations. But during Einstein's lifetime only one such object was known: the universe taken as a whole.

Einstein with de Sitter.

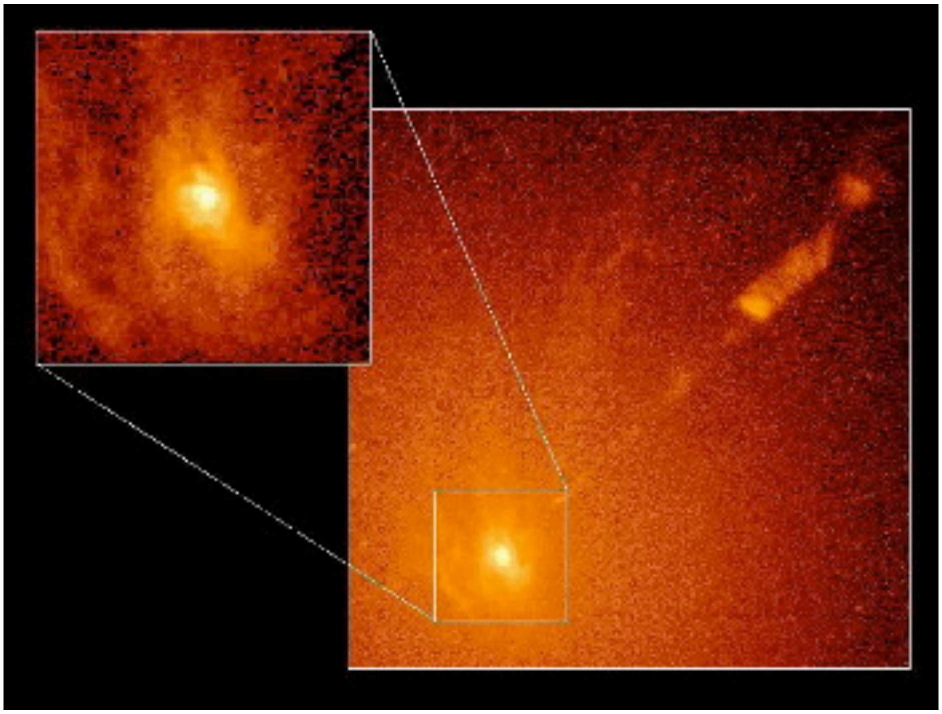
In 1917 Einstein and the Dutch astronomer Willem de Sitter showed that Einstein's equations could be used to describe a highly simplified universe. Other scientists developed this model, adapting it to the real universe full of stars. They found a difficulty: the model had to show the stars either all moving apart, as if from a giant explosion, or all collapsing together upon each other. But Einstein had found room in his equations for an extra mathematical term, the "cosmological term" as he called it. He could adjust this term to give a new model: an unchanging model universe.

Hubble at his telescope.

In 1929 the American astronomer Edwin Hubble discovered evidence that distant galaxies of stars are moving away from our galaxy, and away from each other, as if the entire universe were expanding. The original Einstein equations might give an exact description of our universe after all. Quickly convinced by Hubble's evidence, Einstein felt that his notion of a "cosmological term" was a mistake. Other scientists withheld judgment, and debate over the cosmological term still continues today. But most astronomers agree that with or without the cosmological term, Einstein's equations give the best available language for a description of the overall structure of the universe.

"I want to know how God created this world. I am not interested in this or that phenomenon, in the spectrum of this or that element. I want to know His thoughts; the rest are details."

A Black Hole...

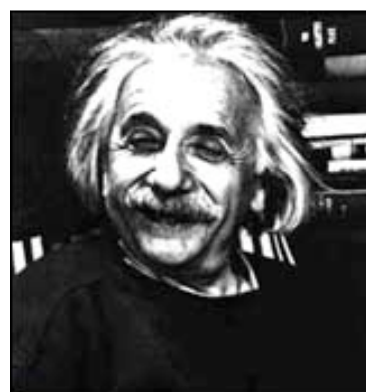


You can't see a black hole itself. Einstein's equations show that where mass is concentrated to an extreme, space closes in upon itself until not even light can escape the gravitational pull. But you can see matter glowing with heat as it falls in. This picture taken by the Hubble Space Telescope shows a whirlpool of hot gas orbiting an astonishing object in the middle of the distant galaxy M87.

Measurements of the gas velocities show that the object must be as massive as three billion suns, all concentrated in a volume no larger than our solar system. Astronomers were pointed to the object by a long jet of gas (upper right), somehow spurted out by the knot of fierce energies generated as other matter falls into the black hole.

Courtesy NASA

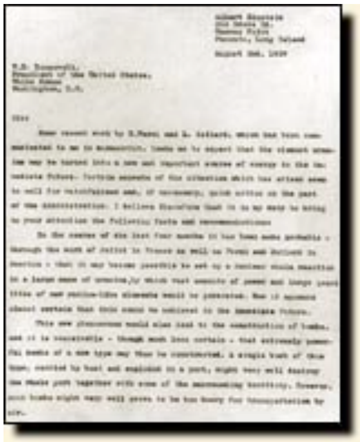
The Quantum and the Cosmos : At Home



"I am happy because I want nothing from anyone. I do not care for money. Decorations, titles, or distinctions mean nothing to me. I do not crave praise. The only thing that gives me pleasure, apart from my work, my violin, and my sailboat, is the appreciation of my fellow workers."

The Nuclear Age

"Concern for man himself must always constitute the chief objective of all technological effort -- concern for the big, unsolved problems of how to organize human work and the distribution of commodities in such a manner as to assure that the results of our scientific thinking may be a blessing to mankind, and not a curse."



Einstein's letter to FDR regarding the possibility of the creation of a nuclear bomb

A postwar reconstruction of the signing of the letter.

Scientists in the 1930s, using machines that could break apart the nuclear cores of atoms, confirmed Einstein's formula $E=mc^2$. The release of energy in a nuclear transformation was so great that it could cause a detectable change in the mass of the nucleus. But the study of nuclei -- in those years the fastest growing area of physics -- had scant effect on Einstein. Nuclear physicists were gathering into ever-larger teams of scientists and technicians, heavily funded by governments and foundations, engaged in experiments using massive devices. Such work was alien to Einstein's habit of abstract thought, done alone or with a mathematical assistant. In return, experimental nuclear physicists in the 1930s had little need for Einstein's theories.

In August 1939 nuclear physicists came to Einstein, not for scientific but for political help. The fission of the uranium nucleus had recently been discovered. A long-time friend, Leo Szilard, and other physicists realized that uranium might be used for enormously devastating bombs. They had reason to fear that Nazi Germany might construct such weapons. Einstein, reacting to the danger from Hitler's aggression, had already abandoned his strict pacifism. He now signed a letter that was delivered to the American president, Franklin D. Roosevelt, warning him to take action. This letter, and a second Einstein-Szilard letter of March 1940, joined efforts by other scientists to prod the United States government into preparing for nuclear warfare. Einstein played no other role in the nuclear bomb project. As a German who had supported left-wing causes, he was denied security clearance for such sensitive work. But during the war he did perform useful service as a consultant for the United States Navy's Bureau of Ordnance.

The Nuclear Age II

"The feeling for what ought and ought not to be grows and dies like a tree, and no fertilizer of any kind will do much good. What the individual can do is give a fine example, and have the courage to firmly uphold ethical convictions in a society of cynics. I have for a long time tried to conduct myself this way, with varying success."

After the Japanese surrendered under nuclear bombardment, Einstein was often in the public eye. In May 1946 he became chairman of the newly formed Emergency Committee of Atomic Scientists, joining their drive for international and civilian control of nuclear energy. He recorded fund-raising radio messages for the group, and wrote a widely read article on their work. Einstein's appeals for nuclear disarmament had an influence among both scientists and the general public. He also spoke out in opposition to German rearmament, defended conscientious objectors against military service, and criticized the Cold War policies of the United States. An early and firm supporter of the United Nations, he was convinced that the solution to international conflict was world law, world government, and a strong world police force. "I am opposed to the use of force under any circumstances, except when confronted by an enemy who pursues the destruction of life as an end in itself."

'Refuse to Testify,' Einstein Advises Intellectuals Called In by Congress

Like many in the 1950s who supported liberal causes, Einstein was suspected of disloyalty. He publicly opposed such McCarthyism. Asked how intellectuals should respond, he declared, "I can only see the revolutionary way of non-cooperation."

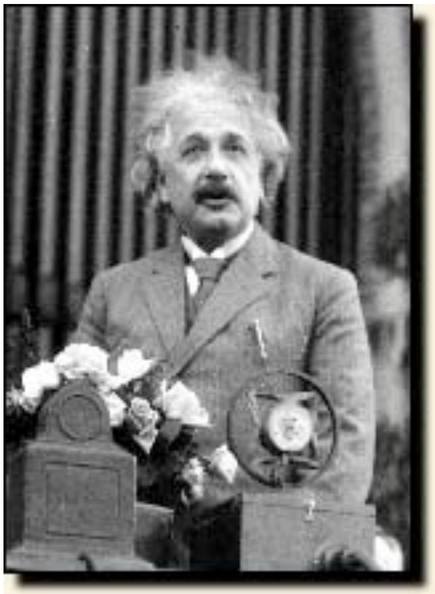
"Here, then, is the problem which we present to you, stark and dreadful and inescapable: Shall we put an end to the human race or shall mankind renounce war? People will not face this alternative because it is so difficult to abolish war."

Although his activity was limited by advancing age and ill health, Einstein made clear his commitment to civil liberties. He attacked racial prejudice and supported the black civil rights movement. He called for a homeland in Palestine for the Jewish people, in which the rights of Arabs would also be respected. Meanwhile, he supported the creation of a Jewish university in the United States (the future Brandeis University). When the House Committee on Un-American Activities maligned teachers and other intellectuals, Einstein publicly advised the people under attack not to cooperate, but to follow the principle of civil disobedience. He was equally uncompromising when he refused any association with Germany. He even rejected honors from his native land -- he could not forgive the murder of Jews by Germans.

In 1952 Einstein was offered the position of President of Israel, a chiefly honorific post. Old and sick, but at peace in his Princeton home and office, he turned down the invitation. His interest in public affairs, however, continued. In 1955 he joined Bertrand Russell in urging scientists toward mediation between East and West and limitation of nuclear armament. Meanwhile he was writing a speech for the anniversary of Israel's independence. An incomplete draft of the speech was found at his bedside after he died.

"The abolition of war will demand distasteful limitations to national sovereignty. But what perhaps impedes understanding of the situation more than anything else is that the term mankind feels vague and abstract. People... can scarcely bring themselves to grasp that they, individually, and those whom they love are in imminent danger of perishing agonizingly. And so they hope that perhaps war may be allowed to continue... this hope is illusory."

Einstein Speaks on Nuclear Weapons and World Peace...



"Today, the physicists who participate in watching the most formidable and dangerous weapon of all time... cannot desist from warning and warning again: we cannot and should not slacken in our efforts to make the nations of the world and especially their governments aware of the unspeakable disaster they are certain to provoke unless they change their attitude towards each other and towards the task of shaping the future. We helped in creating this new weapon in order to prevent the enemies of mankind from achieving it ahead of us. Which, given the mentality of the Nazis, would have meant inconceivable destruction, and the enslavement of the rest of the world...

Large parts of the world are faced with starvation, while others are living in abundance. The nations were promised liberation and justice, but we have witnessed and are witnessing, even now, the sad spectacle of liberating armies firing into populations who want their independence and social equality, and supporting in those countries by force of arms, such parties and personalities as appear to be most suited to serve vested interests. Territorial questions and arguments of power, obsolete though they are, still prevail over the essential demands of common welfare and justice."

Nuclear Age : At Home

"I have journeyed to and fro continuously -- a stranger everywhere... A person like me has as his ideal to be at home somewhere with his family."

Einstein's first wife and their sons.

At home in Berlin

Einstein with his second wife, Elsa, and her daughter.

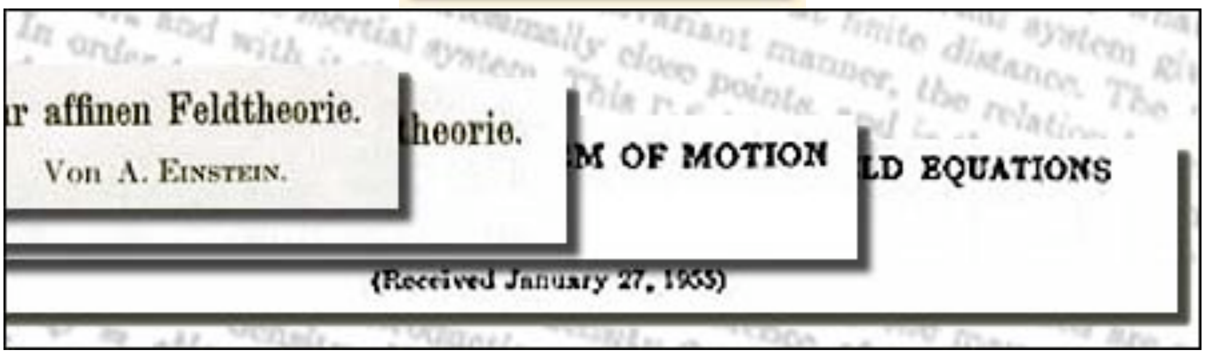
Einstein's home in Princeton.

"I have settled down splendidly here: I hibernate like a bear in its cave, and really feel more at home than ever before in my life with all its changes."

At home in Princeton.

Science and Philosophy I

"One thing I have learned in a long life: that all our science, measured against reality, is primitive and childlike -- and yet it is the most precious thing we have."



Several of Einstein's *papers on unified field theory*.

From before 1920 until his death in 1955, Einstein struggled to find laws of physics far more general than any known before. In his theory of relativity, the force of gravity had become an expression of the geometry of space and time. The other forces in nature, above all the force of electromagnetism, had not been described in such terms. But it seemed likely to Einstein that electromagnetism and gravity could both be explained as aspects of some broader mathematical structure. The quest for such an explanation -- for a "unified field" theory that would unite electromagnetism and gravity, space and time, all together -- occupied more of Einstein's years than any other activity.

With Peter Bergmann and Leopold Infeld.

"I see in Nature a magnificent structure... that must fill a thinking person with a feeling of humility..."

Can the Laws of Physics be Unified?

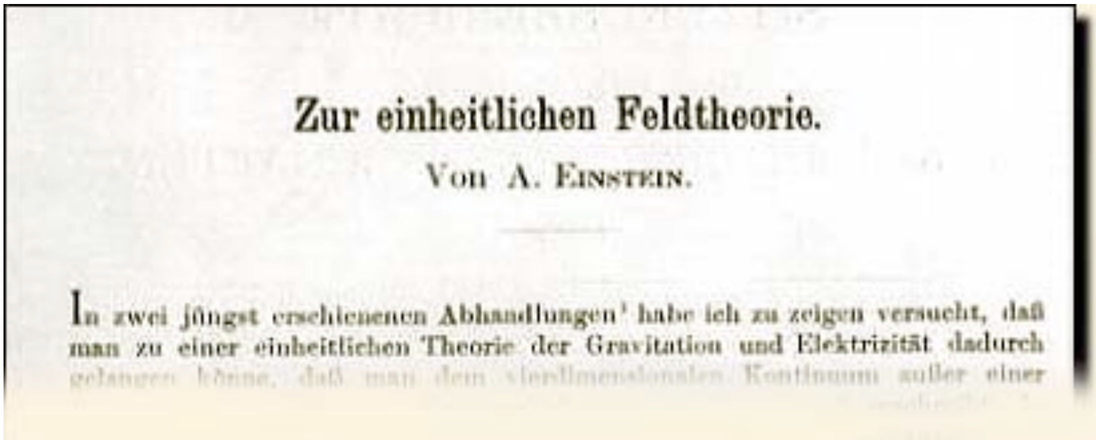
The particle accelerator at CERN, in a 27-km circular tunnel near Geneva. This is the biggest of the "atom smashers" that blast matter into its most fundamental fragments.

Physicists have not yet found a single, elegant set of laws describing all the fundamental forces of nature. But since Einstein's day they have made important progress. Experiments using particle accelerators have pointed the way to new mathematical rules, which cover both electromagnetic forces and the nuclear forces that shape the cores of atoms. These rules leave much to be explained, but they do predict almost everything about the elementary behavior of material particles.

Everything but gravity. Nobody has found a way to fit Einstein's curved space together with the wholly different quantum approach that works for electromagnetic and nuclear forces. Recently some physicists proposed a third approach: "string theory." They picture fundamental particles as tiny loops, which vibrate like violin strings in a fantastic multi-dimensional space. Surprisingly, gravitation emerges from these equations as a natural by-product.

However, nobody has found a way to test string theory experimentally. Unless that can be done the theory will remain, like Einstein's attempts at unified field equations, a hopeful curiosity.

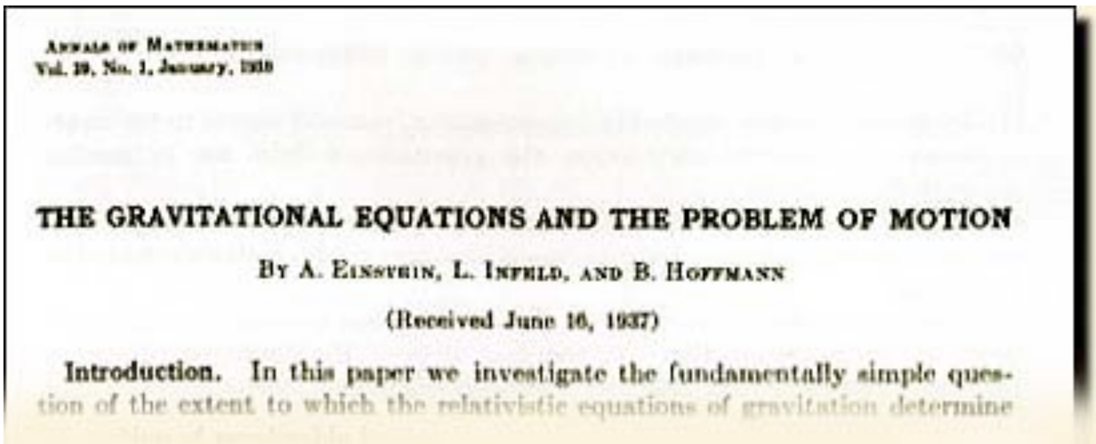
Image courtesy CERN



Zur einheitlichen Feldtheorie.

Von A. Einstein.

In zwei jüngst erschienenen Abhandlungen[1] habe ich zu zeigen versucht, daß man zu einer einheitlichen Theorie der Gravitation und Elektrizität dadurch gelangen könne, daß man dem vierdimensionalen Kontinuum außer einer



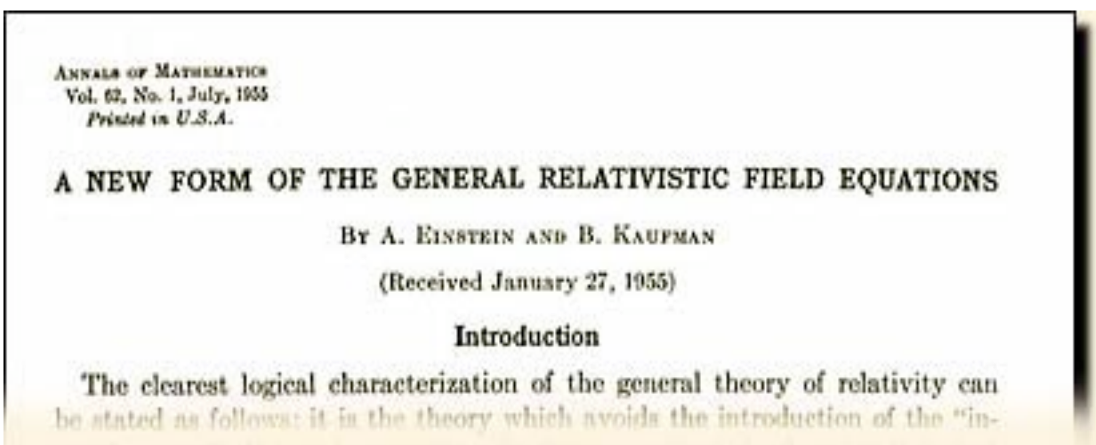
Annals of Mathematics
Vol. 39, No. 1, January, 1938

THE GRAVITATIONAL EQUATIONS AND THE PROBLEM OF MOTION

By A. Einstein, L. Infeld, and B. Hoffmann

(Received June 16, 1937)

Introduction. In this paper we investigate the fundamentally simple question of the extent to which the relativistic equations of gravitation determine



Annals of Mathematics
Vol. 62, No. 1, July, 1955
Printed in U.S.A.

A NEW FORM OF THE GENERAL RELATIVISTIC FIELD EQUATIONS

By A. Einstein and B. Kaufman

(Received January 27, 1955)

Introduction

The clearest logical characterization of the general theory of relativity can be stated as follows: it is the theory which avoids the introduction of the "in-

Einstein switched from German to English publication when he moved to the United States. This corresponded to a historic shift from German to American dominance in all of physics -- resulting partly from a long-term rise of American universities, and partly from the decline of German ones under Nazi attack. Notice too the shift to collaborative writing.

Science and Philosophy II

Einstein lecturing in Princeton.

Einstein thought that if only he could find the right unified field theory, that theory might also explain the structure of matter. Thus he could fill the troubling gap in quantum theory -- the inability to describe the world otherwise than in terms of mere probabilities. He doubted his ability to find this "more complete theory," but he was convinced that someday, somebody would find it. "I cannot," he admitted, "base this conviction on logical reasons -- my only witness is the pricking of my little finger."

Over the years Einstein proposed unified field theories in various mathematical forms. Flaws were detected in his theories one by one, usually by Einstein himself. Undiscouraged, he would try new formulations, only to see them fail in turn. Sooner or later most of the other scientists who had joined the search gave it up. Einstein kept on, aware that many of his colleagues thought he was pursuing a will-o'-the wisp. One young physicist described him as a luminary shining in helpless isolation. Einstein knew better than anyone the limitations of his efforts, but the relentless work held a "fascinating magic" for him. "One cannot help but be in awe when one contemplates the mysteries of eternity, of life, of the marvelous structure of reality," he wrote. "It is enough if one tries merely to comprehend a little of this mystery each day." With this credo Einstein had already given humanity a new view of the physical universe, and a model for what a person of conscience may achieve.

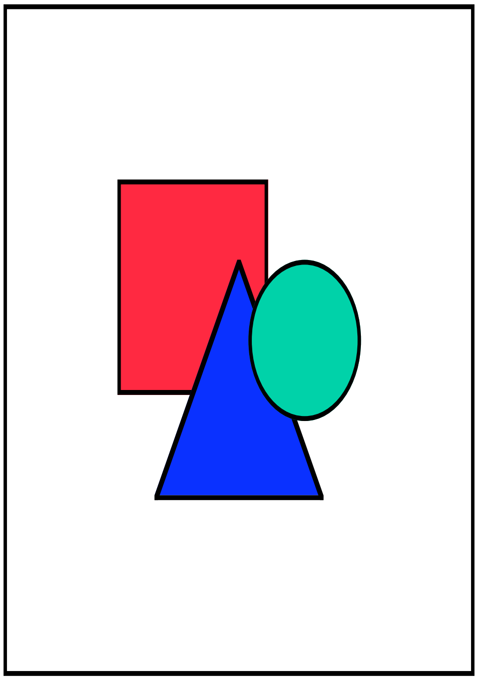
"Never lose a holy curiosity."

"The essential in the existence of a man like me is what he thinks and how he thinks, not what he does or suffers."

Einstein's blackboard after his death.

The World As I See It

An Essay By Einstein



"How strange is the lot of us mortals! Each of us is here for a brief sojourn; for what purpose he knows not, though he sometimes thinks he senses it. But without deeper reflection one knows from daily life that one exists for other people -- first of all for those upon whose smiles and well-being our own happiness is wholly dependent, and then for the many, unknown to us, to whose destinies we are bound by the ties of sympathy. A hundred times every day I remind myself that my inner and outer life are based on the labors of other men, living and dead, and that I must exert myself in order to give in the same measure as I have received and am still receiving...

"I have never looked upon ease and happiness as ends in themselves -- this critical basis I call the ideal of a pigsty. The ideals that have lighted my way, and time after time have given me new courage to face life cheerfully, have been Kindness, Beauty, and Truth. Without the sense of kinship with men of like mind, without the occupation with the objective world, the eternally unattainable in the field of art and scientific endeavors, life would have seemed empty to me. The trite objects of human efforts -- possessions, outward success, luxury -- have always seemed to me contemptible.

"My passionate sense of social justice and social responsibility has always contrasted oddly with my pronounced lack of need for direct contact with other human beings and human communities. I am truly a 'lone traveler' and have never belonged to my country, my home, my friends, or even my immediate family, with my whole heart; in the face of all these ties, I have never lost a sense of distance and a need for solitude..."

"My political ideal is democracy. Let every man be respected as an individual and no man idolized. It is an irony of fate that I myself have been the recipient of excessive admiration and reverence from my fellow-beings, through no fault, and no merit, of my own. The cause of this may well be the desire, unattainable for many, to understand the few ideas to which I have with my feeble powers attained through ceaseless struggle. I am quite aware that for any organization to reach its goals, one man must do the thinking and directing and generally bear the responsibility. But the led must not be coerced, they must be able to choose their leader. In my opinion, an autocratic system of coercion soon degenerates; force attracts men of low morality... The really valuable thing in the pageant of human life seems to me not the political state, but the creative, sentient individual, the personality; it alone creates the noble and the sublime, while the herd as such remains dull in thought and dull in feeling.

"This topic brings me to that worst outcrop of herd life, the military system, which I abhor... This plague-spot of civilization ought to be abolished with all possible speed. Heroism on command, senseless violence, and all the loathsome nonsense that goes by the name of patriotism -- how passionately I hate them!

"The most beautiful experience we can have is the mysterious. It is the fundamental emotion that stands at the cradle of true art and true science. Whoever does not know it and can no longer wonder, no longer marvel, is as good as dead, and his eyes are dimmed. It was the experience of mystery -- even if mixed with fear -- that engendered religion. A knowledge of the existence of something we cannot penetrate, our perceptions of the profoundest reason and the most radiant beauty, which only in their most primitive forms are accessible to our minds: it is this knowledge and this emotion that constitute true religiosity. In this sense, and only this sense, I am a deeply religious man... I am satisfied with the mystery of life's eternity and with a knowledge, a sense, of the marvelous structure of existence -- as well as the humble attempt to understand even a tiny portion of the Reason that manifests itself in nature."

See also Einstein's Third Paradise, an essay by Gerald Holton

The text of Albert Einstein's copyrighted essay, "The World As I See It," was shortened for our Web exhibit. The essay was originally published in "Forum and Century," vol. 84, pp. 193-194, the thirteenth in the Forum series, Living Philosophies. It is also included in Living Philosophies (pp. 3-7) New York: Simon Schuster, 1931. For a more recent source, you can also find a copy of it in A. Einstein, Ideas and Opinions, based on Mein Weltbild, edited by Carl Seelig, New York: Bonzana Books, 1954 (pp. 8-11).

Einstein's Third Paradise

By Gerald Holton

Historians of modern science have good reason to be grateful to Paul Arthur Schilpp, professor of philosophy and Methodist clergyman but better known as the editor of a series of volumes on "Living Philosophers," which included several volumes on scientist-philosophers. His motto was: "The asking of questions about a philosopher's meaning while he is alive." And to his everlasting credit, he persuaded Albert Einstein to do what he had resisted all his years: to sit down to write, in 1946 at age sixty-seven, an extensive autobiography – forty-five pages long in print.

To be sure, Einstein excluded there most of what he called "the merely personal." But on the very first page he shared a memory that will guide us to the main conclusion of this essay. He wrote that when still very young, he had searched for an escape from the seemingly hopeless and demoralizing chase after one's desires and strivings. That escape offered itself first in religion. Although brought up as the son of "entirely irreligious (Jewish) parents," through the teaching in his Catholic primary school, mixed with his private instruction in elements of the Jewish religion, Einstein found within himself a "deep religiosity"– indeed, "the religious paradise of youth."

The accuracy of this memorable experience is documented in other sources, including the biographical account of Einstein's sister, Maja. There she makes a plausible extrapolation: that Einstein's "religious feeling" found expression in later years in his deep interest and actions to ameliorate the difficulties to which fellow Jews were being subjected, actions ranging from his fights against anti-Semitism to his embrace of Zionism (in the hope, as he put it in one of his speeches [April 20, 1935], that it would include a "peaceable and friendly cooperation with the Arab people"). As we shall see, Maja's extrapolation of the reach of her brother's early religious feelings might well have gone much further.

The primacy of young Albert's First Paradise came to an abrupt end. As he put it early in his "Autobiographical Notes," through reading popular science books he came to doubt the stories of the Bible. Thus he passed first through what he colorfully described as a "positively fanatic indulgence in free thinking."[1] But then he found new enchantments. First, at age twelve, he read a little book on Euclidean plane geometry – he called it "holy," a veritable "Wunder." Then, still as a boy, he became entranced by the contemplation of that huge external, extra-personal world of science, which presented itself to him "like a great, eternal riddle." To that study one could devote oneself, finding thereby "inner freedom and security." He believed that choosing the "road to this Paradise," although quite antithetical to the first one and less alluring, did prove itself trustworthy. Indeed, by age sixteen, he had his father declare him to the authorities as "without confession," and for the rest of his life he tried to dissociate himself from organized religious activities and associations, inventing his own form of religiousness, just as he was creating his own physics.

These two realms appeared to him eventually not as separate as numerous biographers would suggest. On the contrary, my task here is to demonstrate that at the heart of Einstein's mature identity there developed a fusion of his First and his Second Paradise – into a Third Paradise, where the meaning of a life of brilliant scientific activity drew on the remnants of his fervent first feelings of youthful religiosity.

For this purpose, we shall have to make what may seem like an excursus, but one that will in the end throw light on his overwhelming passion, throughout his scientific and personal life, to bring about the joining of these and other seemingly incommensurate aspects, whether in nature or society. In 1918 he gave a glimpse of it in a speech ("*Prinzipien der Forschung*") honoring the sixtieth birthday of his friend and colleague Max Planck, to whose rather metaphysical conception about the purpose of science Einstein had drifted while moving away from the quite opposite, positivistic one of an early intellectual mentor, Ernst Mach. As Einstein put it in that speech, the search for one "simplified and lucid image of the world" not only was the supreme task for a scientist, but also corresponded to a psychological need: to flee from personal, everyday life, with all its dreary disappointments, and escape into the world of objective perception and thought. Into the formation of such a world picture the scientist could place the "center of gravity of his emotional life [*Gefühlsleben*]." And in a sentence with special significance, he added that persevering on the most difficult scientific problems requires "a state of feeling [*Gefühlszustand*] similar to that of a religious person or a lover."

Throughout Einstein's writings, one can watch him searching for that world picture, for a comprehensive Weltanschauung, one yielding a total conception that, as he put it, would include every empirical fact (*Gesamtheit der Erfahrungstatsachen*) – not only of physical science, but also of life.

Einstein was of course not alone in this pursuit. The German literature of the late nineteenth and early twentieth centuries contained a seemingly obsessive flood of books and essays on the oneness of the world picture. They included writings by both Ernst Mach and Max Planck, and, for good measure, a 1912 general manifesto appealing to scholars in all fields of knowledge to combine their efforts in order to "bring forth a comprehensive Weltanschauung." The thirty-four signatories included Ernst Mach, Sigmund Freud, Ferdinand Tonnies, David Hilbert, Jacques Loeb. and the then still little-known Albert Einstein.

But while for most others this culturally profound longing for unity – already embedded in the philosophical and literary works they all had studied – was mostly the subject of an occasional opportunity for exhortation (nothing came of the manifesto), for Einstein it was different, a constant preoccupation responding to a persistent, deeply felt intellectual and psychological need.

This fact can be most simply illustrated in Einstein's scientific writings. As a first example, I turn to one of my favorite manuscripts in his archive. It is a lengthy manuscript in his handwriting, of around 1920, titled, in translation, "Fundamental Ideas and Methods of Relativity." It contains the passage in which Einstein revealed what in his words was "the happiest thought of my life" [*der gluecklichste Gedanke meines Lebens*] – a thought experiment that came to him in 1907: nothing less than the definition of the equivalence principle, later developed in his general relativity theory. It occurred to Einstein – thinking first of all in visual terms, as was usual for him – that if a man were falling from the roof of his house and tried to let anything drop, it would only move alongside him, thus indicating the equivalence of acceleration and gravity. In Einstein's words, "the acceleration of free fall with respect to the material is therefore a mighty argument that the postulate of relativity is to be extended to coordinate systems that move nonuniformly relative to one another . . . ."

For the present purpose I want to draw attention to another passage in that manuscript. His essay actually begins in a largely impersonal, pedagogic tone, similar to that of his first popular book on relativity, published in 1917. But in a surprising way, in the section titled "General Relativity Theory," Einstein suddenly switches to a personal account. He reports that in the construction of the special theory, the "thought concerning the Faraday [experiment] on electromagnetic induction played for me a leading role." He then describes that old experiment, in words similar to the first paragraph of his 1905 relativity paper, concentrating on the well-known fact, discovered by Faraday in 1831, that the induced current is the same whether it is the coil or the magnet that is in motion relative to the other, whereas the "theoretical interpretation of the phenomenon in these two cases is quite different." While other physicists, for many decades, had been quite satisfied with that difference, here Einstein reveals a central preoccupation at the depth of his soul: "The thought that one is dealing here with two fundamentally different cases was for me unbearable [*war mir unertraeglich*]. The difference between these two cases could not be a real difference . . . . The phenomenon of the electromagnetic induction forced me to postulate the (special) relativity principle."

Let us step back for a moment to contemplate that word "unbearable." It is reinforced by a passage in Einstein's "Autobiographical Notes": "By and by I despaired [*verzweifelte ich*] of discovering the true laws by means of constructive efforts based on known facts. The longer and the more despairingly I tried, the more I came to the conviction that only the discovery of a universal formal principle could lead us to assured results." He might have added that the same postulational method had already been pioneered in their main works by two of his heroes, Euclid and Newton. Other physicists, for example Bohr and Heisenberg, also reported that at times they were brought to despair in their research. Still other scientists were evidently even brought to suicide by such disappointment. For researchers fiercely engaged at the very frontier, the psychological stakes can be enormous. Einstein was able to resolve his discomfort by turning, as he did in his 1905 relativity paper, to the *postulation* of two formal principles (the principle of relativity throughout physics, and the constancy of the velocity of light in vacuo), and adopting such postulations as one of his tools of thought.

Einstein also had a second method to bridge the unbearable differences in a theory: *generalizing it*, so that the apparently differently grounded phenomena are revealed to be coming from the same base. We know from a letter to Max von Laue of January 17, 1952, found in the archive, that Einstein's early concern with the physics of fluctuation phenomena was the common root of his three great papers of 1905, on such different topics as the quantum property of light, Brownian movement, and relativity. But even earlier, in a letter of April 14, 1901, to his school friend Marcel Grossmann, Einstein had revealed his generalizing approach to physics while working on his very first published paper, on capillarity. There he tried to bring together in one theory the opposing behaviors of bodies: moving upward when a liquid is in a capillary tube, but downward when the liquid is released freely. In that letter, he spelled out his interpenetrating emotional and scientific needs in one sentence: "It is a wonderful feeling [*ein herrliches Gefuhl*] to recognize the unity of a complex of appearances which, to direct sense experiences, appear to be quite separate things."

The postulation of universal formal principles, and the discovery among phenomena of a unity, of *Einheitlichkeit*, through the *generalization* of the basic theory – those were two of Einstein's favorite weapons,[2] as his letters and manuscripts show. Writing to Willem de Sitter on November 4, 1916, he confessed: "I am driven by my need to generalize [*mein Verallgemeinerungsbeduerfnis*]." That need, that compulsion, was also deeply entrenched in German culture and resonated with, and supported, Einstein's approach. Let me just note in passing that while still a student at the Polytechnic Institute in Zurich, in order to get his certificate to be a high school science teacher, Einstein took optional courses on Immanuel Kant and Goethe, whose central works he had studied since his teenage years.

That *Verallgemeinerungsbeduerfnis* was clearly a driving force behind Einstein's career trajectory. Thus he generalized from old experimental results, like Faraday's, to arrive at special relativity, in which he unified space and time, electric and magnetic forces, energy and mass, and so resolved the whole long dispute among scientists between adherence to a mechanistic versus an electromagnetic world picture. Then he generalized the special theory to produce what he first significantly called, in an article of 1913, not the *general* but the *generalized relativity theory*. Paul Ehrenfest wrote him in puzzlement: "How far will this *Verallgemeinerung* go on?" And, finally, Einstein threw himself into the attempt of a grand unification of quantum physics and of gravity: a unified field theory. It is an example of an intense and perhaps unique, life-long, tenacious dedication, despite Einstein's failure at the very end – which nevertheless, as a program, set the stage for the ambition of some of today's best scientists, who have taken over that search for the Holy Grail of physics – a theory of everything.

So much for trying to get a glimpse of the mind of Einstein as scientist. But at this point, for anyone who has studied this man's work and life in detail, a new thought urges itself forward. As in his science, Einstein also lived under the compulsion to unify – in his politics, in his social ideals, even in his everyday behavior. He abhorred all nationalisms, and called himself, even while in Berlin during World War I, a European. Later he supported the One World movement, dreamed of a unified supernational form of government, helped to initiate the international Pugwash movement of scientists during the Cold War, and was as ready to befriend visiting high school students as the Queen of the Belgians. His instinctive penchant for democracy and dislike of hierarchy and class differences must have cost him greatly in the early days, as when he addressed his chief professor at the Swiss Polytechnic Institute, on whose recommendation his entrance to any academic career would depend, not by any title, but simply as "Herr Weber." And at the other end of the spectrum, in his essay on ethics, Einstein cited Moses, Jesus, and Buddha as equally valid prophets.

No boundaries, no barriers; none in life, as there are none in nature. Einstein's life and his work were so mutually resonant that we recognize both to have been carried on together in the service of one grand project – the fusion into one coherency.

There were also no boundaries or barriers between Einstein's scientific and religious feelings. After having passed from the youthful first, religious paradise into his second, immensely productive scientific one, he found in his middle years a fusion of those two motivations – his Third Paradise.

We had a hint of this development in his remark in 1918, where he observed the parallel states of feeling of the scientist and of the "religious person." Other hints come from the countless, well known quotations in which Einstein referred to God – doing it so often that Niels Bohr had to chide him. Karl Popper remarked that in conversations with Einstein, "I learned nothing . . . . he tended to express things in theological terms, and this was often the only way to argue with him. I found it finally quite uninteresting."

But two other reports may point to the more profound layer of Einstein's deepest convictions. One is his remark to one of his assistants, Ernst Straus: "What really interests me is whether God had any choice in the creation of the world." The second is Einstein's reply to a curious telegram.

In 1929, Boston's Cardinal O'Connell branded Einstein's theory of relativity as "befogged speculation producing universal doubt about God and His Creation," and as implying "the ghastly apparition of atheism." In alarm, New York's Rabbi Herbert S. Goldstein asked Einstein by telegram: "Do you believe in God? Stop. Answer paid 50 words." In his response, for which Einstein needed but twenty-five (German) words, he stated his beliefs succinctly: "I believe in Spinoza's God, Who reveals Himself in the lawful harmony of the world, not in a God Who concerns Himself with the fate and the doings of mankind." The rabbi cited this as evidence that Einstein was not an atheist, and further declared that "Einstein's theory, if carried to its logical conclusion, would bring to mankind a scientific formula for monotheism." Einstein wisely remained silent on that point.

The good rabbi might have had in mind the writings of the Religion of Science movement, which had flourished in Germany under the distinguished auspices of Ernst Haeckel, Wilhelm Ostwald, and their circle (the *Monistenbund*), and also in America, chiefly in Paul Carus's books and journals, such as *The Open Court*, which carried the words "Devoted to the Religion of Science" on its masthead.

If Einstein had read Carus's book, *The Religion of Science* (1893), he may have agreed with one sentence in it: "Scientific truth is not profane, it is sacred." Indeed, the charismatic view of science in the lives of some scientists has been the subject of much scholarly study, for example in Joseph Ben-David's *Scientific Growth* (1991), and earlier in Robert K. Merton's magisterial book of 1938, *Science, Technology and Society in Seventeenth-Century England*. In the section entitled "The Integration of Religion and Science," Merton notes that among the scientists he studied, "the religious ethic, considered as a social force, so consecrated science as to make it a highly respected and laudable focus of attention." The social scientist Bernard H. Gustin elaborated on this perception, writing that science at the highest level is charismatic because scientists devoted to such tasks are "thought to come into contact with what is essential in the universe." I believe this is precisely why so many who knew little about Einstein's scientific writing flocked to catch a glimpse of him and to this day feel somehow uplifted by contemplating his iconic image.

Starting in the late 1920s, Einstein became more and more serious about clarifying the relationship between his transcendental and his scientific impulses. He wrote several essays on religiosity; five of them, composed between 1930 and the early 1950s, are reproduced in his book *Ideas and Opinions*. In those chapters we can watch the result of a struggle that had its origins in his school years, as he developed, or rather invented, a religion that offered a union with science.

In the evolution of religion, he remarked, there were three developmental stages. At the first, "with primitive man it is above all fear that evokes religious notions. This 'religion of fear' . . . is in an important degree stabilized by the formation of a special priestly caste" that colludes with secular authority to take advantage of it for its own interest. The next step – "admirably illustrated in the Jewish scriptures" – was a moral religion embodying the ethical imperative, "a development [that] continued in the New Testament." Yet it had a fatal flaw: "the anthropomorphic character of the concept of God," easy to grasp by "underdeveloped minds" of the masses while freeing them of responsibility. This flaw disappears at Einstein's third, mature stage of religion, to which he believed mankind is now reaching and which the great spirits (he names Democritus, St. Francis of Assisi, and Spinoza) had already attained – namely, the "cosmic religious feeling" that sheds all anthropomorphic elements. In describing the driving motivation toward that final, highest stage, Einstein uses the same ideas, even some of the same phrases, with which he had celebrated first his religious and then his scientific paradise: "The individual feels the futility of human desires, and aims at the sublimity and marvelous order which reveal themselves both in nature and in the world of thought." "Individual existence impresses him as a sort of prison, and he wants to experience the universe as a single, significant whole." Of course! Here as always, there has to be the intoxicating experience of unification. And so Einstein goes on, "I maintain that the cosmic religious feeling is the strongest and noblest motive for scientific research . . . . A contemporary has said not unjustly that in this materialistic age of ours the serious scientific workers are the only profoundly religious people."

In another of his essays on religion, Einstein points to a plausible source for his specific formulations: "Those individuals to whom we owe the great creative achievements of science were all of them imbued with a truly religious conviction that this universe of ours is something perfect, and susceptible through the rational striving for knowledge. If this conviction had not been a strongly emotional one, and if those searching for knowledge had not been inspired by Spinoza's *amor dei intellectualis*, they would hardly have been capable of that untiring devotion which alone enables man to attain his greatest achievements."

I believe we can guess at the first time Einstein read Baruch Spinoza's *Ethics* (*Ethica Ordinae Geometrico Demonstrata*), a system constructed on the Euclidean model of deductions from propositions. Soon after getting his first real job at the patent office, Einstein joined with two friends to form a discussion circle, meeting once or twice a week in what they called, with gallows humor, the *Akademie Olympia*. We know the list of books they read and discussed. High among them, reportedly at Einstein's suggestion, was Spinoza's *Ethics*, which he read afterwards several times more. Even when his sister Maja joined him in Princeton in later life and was confined to bed by an illness, he thought that reading a good book to her would help, and chose Spinoza's *Ethics* for that purpose.

By that time Spinoza's work and life had long been important to Einstein. He had written an introduction to a biography of Spinoza (by his son-in-law, Rudolf Kayser, 1946); he had contributed to the *Spinoza Dictionary*

(1951); he had referred to Spinoza in many of his letters; and he even had composed a poem in Spinoza's honor. He admired Spinoza for his independence of mind, his deterministic philosophical outlook, his skepticism about organized religion and orthodoxy – which had resulted in his excommunication from his synagogue in 1656 – and even for his ascetic preference, which compelled him to remain in poverty and solitude to live in a sort of spiritual ecstasy, instead of accepting a professorship at the University of Heidelberg. Originally neglected, Spinoza's *Ethics*, published only posthumously, profoundly influenced other thinkers, such as Friedrich Schlegel, Friedrich Schleiermacher, Goethe (who called him "our common saint"), Albert Schweitzer, and Romain Rolland (who, on reading *Ethics*, confessed, "I deciphered not what he said, but what he meant to say"). For Spinoza, God and nature were one (*deus sive natura*). True religion was based not on dogma but on a feeling for the rationality and the unity underlying all finite and temporal things, on a feeling of wonder and awe that *generates* the idea of God, but a God which lacks any anthropomorphic conception. As Spinoza wrote in Proposition 15 in *Ethics*, he opposed assigning to God "body and soul and being subject to passions." Hence, "God is incorporeal" – as had been said by others, from Maimonides on, to whom God was knowable indirectly through His creation, through nature. In other pages of *Ethics*, Einstein could read Spinoza's opposition to the idea of cosmic purpose, and that he favored the primacy of the law of cause and effect – an all-pervasive determinism that governs nature and life – rather than "playing at dice," in Einstein's famous remark. And as if he were merely paraphrasing Spinoza, Einstein wrote in 1929 that the perception in the universe of "profound reason and beauty constitute true religiosity; in this sense, and in this sense alone, I am a deeply religious man."

Much has been written about the response of Einstein's contemporaries to his Spinozistic cosmic religion. For example, the physicist Arnold Sommerfeld recorded in Schilpp's volume that he often felt "that Einstein stands in a particularly intimate relation to the God of Spinoza." But what finally most interests us here is to what degree Einstein, having reached his Third Paradise, in which his yearnings for science and religion are joined, may even have found in his own research in physics fruitful ideas emerging from that union. In fact there are at least some tantalizing parallels between passages in Spinoza's *Ethics* and Einstein's publications in cosmology – parallels that the physicist and philosopher Max Jammer, in his book *Einstein and Religion* (1999), considers as amounting to intimate connections. For example, in Part I of Ethics ("Concerning God"), Proposition 29 begins: "In nature there is nothing contingent, but all things are determined from the necessity of the divine nature to exist and act in a certain manner." Here is at least a discernible overlap with Einstein's tenacious devotion to determinism and strict causality at the fundamental level, despite all the proofs from quantum mechanics of the reign of probabilism, at least in the subatomic realm.

There are other such parallels throughout. But what is considered by some as the most telling relationship between Spinoza's Propositions and Einstein's physics comes from passages such as Corollary 2 of Proposition 20: "It follows that God is immutable or, which is the same thing, all His attributes are immutable." In a letter of September 3, 1915, to Else (his cousin and later his wife), Einstein, having read Spinoza's *Ethics* again, wrote, "I think the *Ethics* will have a permanent effect on me."

Two years later, when he expanded his general relativity to include "cosmological considerations," Einstein found to his dismay that his system of equations did "not allow the hypothesis of a spatially closed-ness of the world [*raeumliche Geschlossenheit*]." How did Einstein cure this flaw? By something he had done very rarely: making an ad hoc addition, purely for convenience: "We can add, on the left side of the field equation a – for the time being – unknown universal constant, - λ['lambda']." In fact, it seems that not much harm is done thereby. It does not change the covariance; it still corresponds with the observation of motions in the solar system ("as long as λ is small"), and so forth. Moreover, the proposed new universal constant λ also determines the average density of the universe with which it can remain in equilibrium, and provides the radius and volume of a presumed spherical universe.

Altogether a beautiful, immutable universe – one an immutable God could be identified with. But in 1922, Alexander Friedmann showed that the equations of general relativity did allow expansion or contraction. And in 1929 Edwin Hubble found by astronomical observations the fact that the universe does expand. Thus Einstein – at least according to the physicist George Gamow – remarked that "inserting λ was the biggest blunder of my life."

Max Jammer and the physicist John Wheeler, both of whom knew Einstein, traced his unusual ad hoc insertion of λ, nailing down that "spatially closed-ness of the world," to a relationship between Einstein's thoughts and Spinoza's Propositions. They also pointed to another possible reason for it: In Spinoza's writings, one finds the concept that God would not have made an empty world. But in an expanding universe, in the infinity of time, the density of matter would be diluted to zero in the limit. Space itself would disappear, since, as Einstein put it in 1952, "On the basis of the general theory of relativity . . . space as opposed to 'what fills space' . . . had no separate existence."

Even if all of these suggestive indications of an intellectual, emotional, and perhaps even spiritual resonance between Einstein's and Spinoza's writings were left entirely aside, there still remains Einstein's attachment to his "cosmic religion." That was the end point of his own troublesome pilgrimage in religiosity – from his early vision of his First Paradise, through his disillusionments, to his dedication to find fundamental unity within natural science, and at last to his recognition of science as the devotion, in his words, of "a deeply religious unbeliever" – his final embrace of seeming incommensurables in his Third Paradise.

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1. All translations from the original German are this author's, where necessary. [return]
2. A third was his use of freely adopted (non- Kantian) categories, or thematic presuppositions. The prominent ones include unity or unification; logical parsimony and necessity; symmetry; simplicity; causality; completeness of explanation; continuum; and, of course, constancy and invariance. [return]

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Einstein's Time
By Peter Galison

This is the text of "Einstein, Poincaré & Modernity: a Conversation,"
by Peter L. Galison & D. Graham Burnett, from Daedalus *(Spring 2003).*
The dialogue is based on Galison's book *Einstein's Clocks, Poincaré's Maps* *(2003).*

Newton, forgive me . . .
–Albert Einstein, *Autobiographical Notes*

D. GRAHAM BURNETT: Peter, in 1997 you gave a plenary session lecture at the History of Science Society meeting in La Jolla entitled "Relentless Historicism: Machines and Metaphysics." I have a vivid memory of the presentation, which was, I think, the first time you shared with the wider community of historians and philosophers of science your research on Einstein, relativity, and the material culture of time in the fin de siècle. And you turned a lot of heads. Your argument went something like this: At the heart of Einstein's watershed 1905 paper on special relativity the paper that shook the foundations of Newtonian physics lies a "thought experiment' about clock synchronization and the "problem" of simultaneity; there, talking about trains arriving in stations and observers watching their watches, Einstein posed what turn out to be insurmountable challenges to Newton's notion of absolute time (and absolute space). This we knew. But then the talk got juicy: you went on to point out that this thought experiment might not be *merely* a thought experiment, since the business of synchronizing time frames through space was more than just abstruse theoretical physics in the late nineteenth and early twentieth centuries. It was a perfectly real, quotidian, and central preoccupation of railway companies, nation-states, and military planners. The increasing speed of railway travel in the second half of the nineteenth century had made it necessary to codify "time zones" around the world zones of conventionalized simultaneity, where people would ignore local time (say, the "noon" of the sun), and go by the noon on their clocks: a subtle change, but an important one, since it put people across the globe in temporal step. There was no other way to run a railroad. Moreover, the design and manufacture of electrotechnical systems that "distributed" this new coordinated time networks of clocks running in sync was a major precision industry. Looked at in the right way, Einstein's thought experiment bore an uncanny resemblance to a set of wholly practical experiments going on all around him even under his very nose, as he earned his living in the Berne Patent Office reviewing exactly these sorts of time distribution devices. That day in La Jolla you left us with a question: Could we really understand Einstein's 1905 paper without understanding the rise of international time conventions and the technologies of industrial time synchronization? Now you have written a book, *Einstein's Clocks, Poincaré's Maps: Empires of Time,* which delivers on this question and expands your original insight. For readers to whom all this is new, would you start by describing how trains and clocks figure in Einstein's landmark publication?

PETER L. GALISON: Certainly. Perhaps the greatest success of nineteenth-century physics was the prediction (and subsequent demonstration) of the existence of "electric waves." Light was nothing other than such a wave. Suddenly the ancient science of optics became no more than a subfield of electromagnetism. At the same time, this thrilling finding brought with it a puzzle: Physicists of the late nineteenth century, very reasonably, thought that a wave had to be a wave *in something*. After all, waves at the beach are waves in water, sound waves are waves in air, and so on. But light could travel in a vacuum that is, apparently through empty space. This led most everyone to suppose that there had to be a special all pervading (and as yet undiscovered) substance the "ether" permeating everything, everywhere, present even in a vacuum. But experimentalists had no luck finding this elusive medium. Einstein's famous 1905 paper on relativity begins here. Generalizing from failed attempts to "see" the ether (or, more correctly, to see any evidence that the earth was moving "through" it), Einstein decided to scrap the ether altogether, and to go after the problem of the propagation of light in a different way. First, he stipulated that *all* the laws of physics including electricity and magnetism were the same in any constantly moving frame of reference. Then he added a seemingly simple (and modest) second assumption: Light travels at the same speed no matter how fast its source is moving. To anyone thinking of ether this was not so strange: Move your hands at any reasonable speed through a room of still air; once you clap your hands the sound waves propagate through the room at the same speed independent of the original motion of your hands. Maybe light was like that: a lamp moving in the ether simply excited light waves that radiated out at a single speed independent of the motion of the lamp. Yet these two reasonable starting assumptions appeared to contradict one another. Suppose lamps were flying this way and that at various speeds, but that in some frame the light beams from those lamps were all traveling at 186,000 miles per second, just the speed predicted by the equations of electrodynamics. Wouldn't those same beams of light appear to be traveling at *different* speeds when seen from a different, moving frame of reference? If that were so, then the equations of electrodynamics would only be valid in one frame of reference, violating Einstein's first principle. It was to resolve this apparent contradiction that Einstein made his single most dramatic move: he criticized the very idea of time as it was usually understood. In particular, he relentlessly pursued the meaning of "simultaneity." Only by criticizing the foundational notions of time and space could one bring the pieces of the theory that the laws of physics were the same in all constantly moving frames; that light traveled at the same speed regardless of its source into harmony. And this is where the trains and clocks enter. Suppose, Einstein reasoned, that you wanted to know what time a train arrived in a train station. Easy enough: you see where the hand of your watch is at the time the engine pulls up alongside you. But what if you wanted to know when a train was pulling into a *distant* station? How do you know whether an event here is simultaneous with an event there? Einstein insisted that we need a simultaneity fixing procedure, a definite system of exchanging signals between the stations that would take into account the time it took for the signal to get from one station to another. By pursuing this insight, Einstein discovered that two events that were simultaneous in one frame of reference would not be simultaneous in another. Moreover, since a length measurement involves determining the position of the front and back of an object *at the same time,* the relativity of simultaneity meant that *length* was relative as well. By removing the absolutes of space and time, Einstein restructured modern physics.

DGB: So what was at stake here was not only the universal ether, the substrate of the cosmos, but also *time* that absolute, ever unrolling, eternally immutable *flowing,* the Platonic time of which all worldly clocks were mere dilapidations. It was this time that Newton had understood was a necessary condition of his physics, and that he had placed beyond the realm of merely human investigation; it flowed in the "Sensorium of God."

PLG: Just by demanding a conventional clock-and-signal based *procedure* to fix simultaneity, Einstein was breaking with the Newtonian idea of time. For Newton, there was absolute, true, mathematical time that ticked ever constantly the same way for all observers. Clocks all kinds were only pale reflections, approximations to this metaphysical temporality. But Einstein's departure from Newtonian time went further, since once Einstein's starting points are accepted dramatic consequences follow. For instance, if a train travels through our station and the engineer and caboose driver flash their lanterns towards the center of the train (at what we in the station judge to be simultaneous moments), we can ask what happens in the train. We on the station platform say: The mid-train conductor moves *towards* the site where the engine driver had flashed his lantern and *away* from the site where the caboose tender had flashed her lamp. So (say we station-based observers) the middle conductor receives the engine flash first. Since by assumption the middle conductor measures the two flashes as moving at equal velocities from equally separated points of origin, he concludes as night follows day that the two flashes were *not* sent simultaneously. So the two flashes that were simultaneous in the station frame are *not* simultaneous in the moving one. Simultaneity is relative to a frame of reference; it is *not* absolute. From an apparently prosaic starting point about clocks, trains, and light signals, Einstein had smashed one of the very centerpieces of classical physics.

DGB: This is perhaps the Einstein of myth and legend, the knight-errant in the borderlands of metaphysics who slays the last chimera of the crystalline spheres. A searcher in the realm of pure mind, he reconnoiters the

Sensorium of God and finds it empty. But this image, you would remind us, is a distortion of Einstein's character, of what he thought he had done, and of his approach to problems as well, no?

PLG: Einstein, without any doubt, is the best-known scientist ever, and he occupies an astonishingly robust cultural place. He doesn't seem to come into and fall out of fashion as much as he is simply appropriated for new purposes with each generation. But one of the perennial features of Einstein-the-icon is the figure of the great mind living in a world apart, the ultimate loner. No doubt Einstein himself is in some measure responsible for this image, since, in later life, he reflected nostalgically on solitude, isolation, and creativity. For instance, he wrote wistfully of the lighthouse attendant, whose world could be that of undistracted thought. So we think of him as the person who could not quite navigate the physical world, and associate that incapacity with a romantic picture of scientific genius. This in turn leads to an odd rewriting of the way he lived his life and did his work.

DGB: Was the patent office Einstein's "lighthouse"?

PLG: This has generally been the story Einstein at the patent office is the genius at his day job: at best a source of bread and butter, at worst a distraction, but in some deep way irrelevant to understanding his science.

DGB: When did you begin to get a different idea of how the story might be told?

PLG: I was standing at a train station in northern Europe admiring a line of clocks that went along the platform. And I noticed that the minute hands were all at the same point I could just see them all lined up. I thought, "These are wonderful clocks; isn't that impressive that they can make them to hold such regularity?" Then I noticed that the second hands were clicking in synchrony too, which was startling, and I thought, "These can't be that accurate you can't have clocks running like this that are not synchronized in some way, or else they'd get out of phase." Suddenly I wondered if Einstein had paid attention to synchronized clocks in train stations. If he had it would give a very tangible sense to that most famous of all scientific thought experiments in his 1905 paper. It would make his move towards a criticism of absolute time both figurative *and* literal. So I went back and I started poking around and found myself in the midst of an absolutely immense literature on fin-de-siècle timekeeping and clocks. As you know, there was at the time an urgent technological problem of coordinating time along train tracks. More than that: in Europe the center of precision-coordinated timekeeping was Switzerland, and if all this industry was based in Switzerland they must have been processing patents right and left. I went to the patent office, and found myself surrounded by a huge number of patents with diagrams of clocks linked by signals. There were even proposals for patents and articles in the technical journals about clocks linked by radio waves. All this seemed extremely close to the kind of materialization of time that preoccupied Einstein. Of course, the clock factories and inventors had no interest in "frames of reference" or in all the "physics of the ether." But the importance of distributing simultaneity by electromagnetic means was clear to everyone. Here was a technical problem located in Switzerland, centered in Berne, and with ideas coming to a point in Einstein's patent office. It all seemed remarkable; and it is there that I began this work.

DGB: And yet Einstein certainly wasn't the only physicist at the turn of the century preoccupied with time ...

PLG: Not at all. In fact, even as I worked on "Einstein in the Patent Office" (and prepared the paper you mentioned), I kept wondering, "Who else would have, should have, been in this mix? And who else from the physics community would have been concerned with ideas of simultaneity?" There is one other person who cared about simultaneity at least as much as Einstein and earlier and that was Henri Poincaré. He certainly saw that clock coordination was essential for defining what we mean by simultaneity.

DGB: Einstein may be a household name, but the same cannot be said for Poincaré.

PLG: I suppose household name, like time and simultaneity, is a relative concept. In France, Poincaré has long been a hero. Known for his innovations in the qualitative studies of chaotic systems, for his invention of the mathematical theory of topology, for his contributions to mathematical physics, and for his philosophy of conventionalism, Poincaré was without any question the most renowned French scientist of the late nineteenth and early twentieth century. And that, in France, meant he was an extraordinarily visible figure whose books about science, philosophy, and morality were best-sellers. He also wrote dramatically and often about the new theory of relativity to which he contributed importantly. Crucially for our understanding of his ideas of simultaneity, Poincaré was, beginning in the early 1890s, deeply involved in time-distribution networks.

DGB: At the Bureau des Longitudes?

PLG: Yes, where he would serve several terms as president. And this was crucial, because the astronomers and geographers of the Bureau were working intensively with the telegraphic transmission of time. This was not for domestic railroad use or at least not in the first instance. Rather, these engineers and scientists were working at a much higher level of precision. They needed to determine simultaneity so distant observers could determine their relative longitude.

DGB: For cartographic purposes, since longitude measurements are measurements of time?[1]

PLG: Precisely. Their goal was to map the nation, the empire, and then much of the world. Specifically, they aimed to find points of reference for instance, in North Africa, Senegal, Ecuador, and Vietnam from which the further mapping of the interiors could proceed. Maps were important for extraction of ores, for military domination, for the cutting of roads, and the laying of railroad lines. Railroad lines brought in more cable, and therefore more mapping, and so on. All of this constituted a major technical program, a great national moment. And the timing is fascinating. Poincaré really became a public figure starting in 1887 or so. And by 1892 he was involved with the Bureau of Longitude, where he tackled problems of time conventions from the decimalization of the hour to reconciling the longitude of the Paris and Greenwich observatories. I remember staring at these reports from the 1890s, trying to figure out what the Bureau's telegraphic time-finders were doing, and expecting that I'd find that as in the case of Einstein's patent office the fixing of simultaneity was a fairly crude affair. But this work was anything but crude! Instead, I saw that by the 1890s it was altogether routine for the astronomer-engineers to *take into account the time the electrical signal took to go from one place to another*. That, I thought I had assumed was exclusively a preoccupation of physicists and their "relativity." But it turned out that Poincaré's colleagues at the Bureau were precisely worried about this, and their concern is plain as day once you look at their data. Columns in the official reports are labeled: "time of transmission." The engineers even sent their time signals on round-trips to compensate for errors. The more I looked at it, the more specific the connections seemed. So in January 1898, when Poincaré wrote his famous philosophical article "The Measure of Time," introducing the simultaneity convention via the metaphor of telegraphic longitude finders, he had in mind an abstraction but also a concrete procedure. A procedure from next door.

DGB: So here, in a real material network of telegraphic transmissions (assembled for geodetic purposes), lies the whole schematic of "relativistic" physics: As you put it in the book, "*simultaneity is a convention, nothing more than the coordination of clocks by a crossed exchange of electromagnetic signals, taking into account the transit time of the signal.*" This is physics, but it is also technology at the turn of the century. And yet, in a way, Poincaré isn't the guy who "gets" the physics of relativity. Or at least this is how he is usually remembered: He was so close, but he turned away from the more radical interpretation of his thinking, and the real discovery was left to Einstein, no?

PLG: What Poincaré first publishes, in January 1898, is the idea that in principle simultaneity is nothing other than the exchange of signals between clocks, taking into account the time of transfer between the clocks of the electric signal or of light. It is a philosophical point (published in the *Review of Metaphysics and Morals)* that is, on my reading, also deeply technological. Between 1898 and 1900 he doesn't apply the scheme to the physics he thinks of the correction to Newtonian physics as being too small, just another longitude-finder's fix. And the reason that he says it's just another error is because that was how it was being treated by his colleagues in the

Bureau of Longitude. Then, in late 1900, Poincaré was invited to speak at a gathering to honor H. A. Lorentz, perhaps the leading theoretical physicist of the day, and an innovator in the electrodynamics of moving bodies. He was also an admired friend of Poincaré's and a father figure to Einstein so Lorentz was a looming figure in late nineteenth-century physics. Poincaré, preparing for this event during a period when he was involved with the details of the Bureau (and still actively presenting the time coordination idea to philosophers), suddenly sees that he can reinterpret a purely mathematical idea of time in Lorentz's physics as a *physical coordination procedure*. In other words, Poincaré looks at the formal way that Lorentz has dealt with the problem, and he says to himself: "No! Really, this is just the telegraph problem that I had written about philosophically two years before!" From December of 1900, Poincaré put the time coordination procedure into his *physics*. He writes about it, and he lectures about the philosophical significance of the physics of time coordination. So it works out that both Poincaré and Einstein were interested in the problem of the philosophical nature of time, the technical ways in which clocks could be set to distribute time, and the physics of how time should enter the theory of electrodynamics of moving bodies.

DGB: Still, physicists and historians of physics have spilled much ink on why Poincaré "missed" being the first to develop Einstein's version of relativity Poincaré was too conservative, he was too much the mathematician. In your book you try to put this question aside, and having situated both physicists in a broader story a story about how simultaneity was *actually produced* at the turn of the century, as well as its technical and cultural resonance you then return to their different perspectives in the conclusion. For there is still a question, isn't there? Given that they're both in this mix that you describe both preoccupied with the "empires of time" in the realms of technology, physics, and even metaphysics how is it that they come out of it with such different "takes"? As I understand it, your answer would have us put aside the idea that Einstein was the "modern" and Poincaré fell "behind the times." In fact, you even suggest at one point that we can hold them next to each other as representatives of "two modernities." Would you say a little more about this tempting idea?

PLG: In the years following 1905, Einstein and Poincaré were working on many of the same problems, both at the absolute top of the profession, both maintaining massive correspondence with many of the same colleagues and friends (including Lorentz). Both were deeply interested in the philosophy of science, both were writing on the side for popular audiences. These were scientists who in many ways were very similar, and yet they did not exchange a single postcard through the entirety of their lives and neither ever even footnoted the other's work on space and time. It puts one in mind of the way that Freud treated Nietzsche: in some ways they were too close and too alien at the same time. It became unbearable for Freud to approach the work of his predecessor. On special relativity neither Poincaré nor Einstein ever argued with the other; they simply acted as if they lived in parallel but nonintersecting universes. Now Poincaré is often depicted as the reactionary who was too backward to absorb fully the radical thoughts of Einstein. That, I believe, is absolutely the wrong way of thinking about it. Both Einstein and Poincaré were concerned with a new and modern physics and a new and modern world. Poincaré wrote essays and gave many lectures about the new mechanics, always emphasizing the enormous novelty of these changes in physics. It simply is not possible to describe him as simply trying to conserve, to reinstate an older physics. But his idea of what needed to be changed was different. It was not Einstein's.

DGB: You characterize Poincaré as an "ameliorist" at one point.

PLG: Yes, I think he is. In another context his nephew once said of Poincaré that he wanted to "fill in the white spaces on the maps." That really gets at something important. In much of his work, whether it was in mathematics (for instance in his discovery of chaos, where he literally made a new kind of map for mathematics, "Poincaré maps"), or administration (for instance in his work trying to map and track the details of a mining accident), or geodetics (for instance in his directing the surveyors who were representing the surface of the earth), he was always trying to fix things, to fill things in, with a great faith in science. He was the ultimate Third Republic French savant a believer in progress, a believer in using reason to make technical things work, a believer in improving the world and solving its crises. Poincaré saw himself as "reforming" time to save Lorentz's extraordinary new theory.

DGB: And this comes out of his training as an engineer, no? Which is so important to the way you depict him...

PLG: Yes, Poincaré's modernism is exactly the modernism of the progressive, late-nineteenth-century engineer somebody who faced all problems as solvable, from the social and political to the scientific and technical. He even played an important *technical* role in absolving Dreyfus when he reanalyzed the "proof" that Dreyfus had authored an incriminating sheet of paper known as the "bordereau." Poincaré's modernism favored scientific-intuitive understanding (in mathematics as in the physics of the ether) and utterly avoided all reference to the spiritual or mystical. It was a modernism that expected the French to lead a rational and ultimately internationalist reformation of all manner of things from the standard meter on up. As far as Poincaré was concerned, physics had often faced crises and in each instance had or could solve the difficulty by an application of a reparative reason. So it was with space and time. These concepts had to be fixed for physics to survive. Poincaré's own ideas about changing the time concept would, he hoped, repair the theory, just as space had been repaired by Lorentz's assumption that moving objects contracted in their direction of motion. But Poincaré kept the fundamental distinctions between "true time" (in the frame of the ether) and "apparent time" as measured in any other frame of reference. And of course he kept the ether which he thought he needed for a productive, intuitive physics. So, for Poincaré, the reinterpretation of time was a necessary patch to keep Lorentz's theory working, one more idea in the kit of ideas that would fix the broken engine of physics.

DGB: And Einstein?

PLG: Well, Einstein had a different picture of what modern physics should be. Einstein had as his ideal neither a machine on which we would do repairs, nor a set of assumptions that would maximize our human convenience in assembling a theory. Instead, Einstein aimed for a reformulation of physics in which the order of theory itself would mirror the order of the world. If the world of phenomena showed no observable distinction between frames of reference then (so Einstein believed) neither should the theory: a symmetry in the phenomena should show up as a symmetry in the theory. "Apparent time" and "true time" were terms he would never utter. Einstein's ideal of a physical theory was thermodynamics, which began with two simple assumptions: first, that the disorder of a system, the "entropy," always increased. From these starting points you went to town, deriving everything else from them. There was (as far as Einstein was concerned) a classical simplicity to thermodynamics: its two pillars supporting all the other elements of the edifice. And Einstein wanted, here and in many of his other works, to build his theories out of principles in this way. He too chose two starting assumptions for relativity theory: first, any observer moving at a constant speed would have the same laws of physics; second, the speed of light is always constant no matter how fast or in what direction the light source was moving. In order to reconcile these two ideas, he argued, it was necessary to put basic ideas of space and time on a defensible and nonarbitrary footing. So Einstein's idea of time really begins at the beginning of the theory, and is necessary to get off the ground at all in the service of simplifying, unifying, and streamlining the theory. Poincaré's theory was differently epistemological, less concerned with "What can we know of an external Nature, and how can we secure that knowledge?" than with his aim of fixing the theory such that it correctly predicted phenomena while maximizing convenience. Poincaré's modernism aimed at an aggressive program of technical repair; Einstein's at a purifying reformulation. Poincaré fastened on simplicity-for-us, assiduously avoiding reference beyond the human. Einstein's modernism aimed for a kind of depth, a matching between representation and the world not just in predictions but deeper in the theory itself. Einstein, after all, in his later years loved to talk about how much choice God had at the beginning of the universe (not a personal God but an underlying order). Poincaré never even grazed that kind of metaphysics. All that said, it would be gross distortion to treat Poincaré as a reactionary or a failed Einstein. The modernism of Picasso is not the modernism of Pollock; and to force the very different breaks with the past into a single line of progression is to lose sight of history.

DGB: The irony here is that, far from being the wild-haired radical, Einstein is revealed to be, if anything, deeply "classical" in his conception of physics.

PLG: Well, in some ways, Einstein is the *most* classical of classical physicists. He is somebody who saw himself in a way as purifying, simplifying, symmetrizing bringing out elements of a less baroque physics. There are many moments, famous moments, in his career, when he objects to the way physics has turned notably in quantum mechanics. By exploring the relationships of classical physics, by deepening them, and by connecting different domains of thought previously held to be disjunct, Einstein, I believe, saw himself as a kind of radical classicist.

DGB: And yet he was, perhaps despite himself, a kind of time bomb in that classical tradition.

PLG: I think here that Einstein's extraordinary apology to Newton where Einstein writes, in this odd and intimate way, "Newton, verzeih' mir' " [Newton, forgive me] is, in a sense, his coming to terms with the fact that in his pursuit of this purifying classical vision he disrupted it. In a way it is a note to himself a note about his own life trajectory, a note on the transformation that resulted from an attempt to deepen and streamline a classical vision.

DGB: One reading of your book would be that you think you have discovered the "smoking gun" for this very transformation, the smoking gun for nothing less than the theory of relativity itself: Einstein is at his patent desk, looking at diagrams of electromechanical networks for time distribution along railway lines. "Eureka!" he shouts, and he sits down to demolish the idea of absolute time and space. I know that you don't care for this reading, and you don't think this is your story, but it will be tempting for many readers ...

PLG: It is absolutely *not* how I think of the problem not for Poincaré, not for Einstein. Almost all of my work stems from a concern with the strange juxtaposition of the very abstract and the very concrete. This is not a question that is by any means restricted to physics, but physics makes it abruptly clear how suddenly we pass from symbols to materiality. In *Einstein's Clocks, Poincaré's Maps,* I want to get away from two widespread ideas: first, a notion that science proceeds by a kind of Platonic ascension, an evaporative or sublimating process that takes the material into the abstract. Material relations do not eject ideas or produce ideas like ripples on the surface of deep-flowing currents. And here coordinated clocks did not *cause* Einstein to introduce the synchronizing procedure. Telegraphic longitude mapping did not force Poincaré to the simultaneity procedure. Conversely, physics does not advance by pure condensation it would be a terrible distortion to see physics beginning in a realm of pure ideas, and then gradually acquiring the weight of materiality until they stand in corporeal form as the objects of everyday life. So the reason that I find this moment of late-nineteenth and early-twentieth-century contemplation of time so interesting is that it represents *neither* of these unilateral directions (concrete- to-abstract or abstract-to-concrete). Instead there is an extraordinary oscillation back and forth between abstraction and concreteness. I like this mix this high-pressure interaction of material technologies, philosophy, and physics. Each was in play, in different ways, and "simultaneity" was at stake in each domain: in Lorentz's mathematical "local time," in the technological exchange of time signals, in the philosophical critique of absolute time. In their own ways, Poincaré and Einstein were reading philosophy, working at technological projects, grappling with electrodynamics. Einstein certainly knew pieces of what Poincaré had done (how much and exactly when is a longer story). Then came Poincaré's moment in December 1900 (and Einstein's in May 1905) when a statement about what simultaneity *is* suddenly participated in all three arcs the crossing point.

DGB: Technology, metaphysics, physics.

PLG: What interests me about this story is precisely that you can't start to tell it if you think that it's all on one scale, or all is really grounded in only one of these domains. Or rather you see very limited pieces of it while vast blocks of the story become unmotivated, even incomprehensible. So if you tell the story of time coordination as a pure history of ideas then Poincaré's references to telegraphy and telegraphic longitude remain...

DGB: incoherent...

PLG: Incoherent, or, more precisely, they appear as fully abstract thought experiments, with the subject (the ground of the metaphor) chosen arbitrarily. But what is interesting to me about it is that as you start to tell the story, no matter where you start and in some ways you have a choice about where to begin you need the other levels. Otherwise the story contains arbitrary elements: Why, for example, is Poincaré publishing about the same procedure for coordinating time in a journal of philosophy of metaphysics and morals, in the Annals of the Bureau of Longitude, and in the physics publications? I think that the very quick back and forth between scales actually points to a dimensionality of history that simply is wiped out if you try to narrate it from a single line. This is a theme of my work, that the metaphorical and the literal are inextricable: that the literal is always referring outwards metaphorically and the metaphorical flickers back into the literal. Asking about the history of physics leads at some key moments both to very material circumstances and to the ethereal layers of metaphysics as well. In the book, I am constantly trying to avoid the historiography of both sublimation and condensation. Instead, I find a peculiar state of vapor and water known as "critical opalescence" to be a better metaphor for the relationship between the abstract and the concrete. For under particular pressure and temperature, vapor flashes back into liquid and liquid into vapor at every scale, from a few molecules to the whole system. The light that we shine on the opalescent mixture reflects back in every color, at every scale. In the late nineteenth century synchronized time was more like that: debates over synchronizing time debates over the conventionality of time itself took place at the scale of buildings, blocks, cities, countries, and the planet, while at the same time arguments came fast and furious about the philosophical and physical basis of time. What I wanted to know very specifically was how a simple proposition, "time simultaneity is nothing other than the coordination of clocks, taking into account the electrical signal-time between them," could function jointly in this multiplicity of trajectories: physics, metaphysics, technology.

DGB: Where somebody was actually *making that notion real* by creating synchronized zones, by creating coordinated clocks, even as the same proposition was transforming our understanding of the physical world, and, perhaps, our place in it.

PLG: Exactly. In 1899, Poincaré was arguing with Greenwich astronomers about how to get their astronomical clocks synchronized, giving a lecture in which he reinterpreted Lorentz's time concept, and presenting to the philosophers his arguments against absolute space and time. All of this occurred essentially at once no one domain *drove* the others. Precisely the simultaneity of all this presents the historian with two great challenges. One is to show how the domains come together. But the other is to exhibit the quasi-stability of each of these discourses, games, or traditions.

DGB: And to do this we must, as you say, "look up to see down, and down to see up."

PLG: The juxtapositions, the links all this is *historical*. It is now a commonplace for string theorists to think of physics and algebraic geometry "going together"; twenty-five years ago that wasn't obvious at all. For those turn-of-the-century decades it made perfect sense to mingle machines and metaphysics. For us, perhaps, the nearness of things and thoughts seems to have vanished, at least where time is concerned. When Poincaré and Einstein looked into the details of electrical engineering, when they stared at generators, radios, and cables, they saw in them critical problems of physics and philosophy. Conversley, they could hardly consider philosophical questions of time and space without asking about central features of physics or technology.

DGB: With hindsight, we will surely discover that we now have our own "philosophical machines." It is tempting to say that the computer is for us what the clock was for much of the history of science: a machine to think with.

PLG: Moments of critical opalescence in the history of science moments when a huge variety of scales are implicated are not frequent. But the development of the modern computer is such a moment as was the late-nineteenth-century deployment of synchronized clocks. It simply isn't possible to tell the story of information theory, for example, without invoking the history of computation. Conversely, there can be no coherent history of electronic computation without showing in detail how the hardware story crossed with the development of theories of information or theories of brain function.

DGB: But let's pull back for a moment. How does the story you tell in this book fit with larger narratives in the history of clocks and timekeeping? Is Einstein's relativistic time "just" time? Is it the apotheosis of the classic history of technology story about time, that wonderful story of progressive human efforts to push time up out of the dirt and the grass, the pulse of the blood and the organic cycles of days and seasons, and to create instead an abstract, disembodied, "pure" time a flowing that would be monitored with fantastically precise devices, devices so precise that they would become critical tools of investigation of nature, and reveal and measure, through time, the myriad quirks and wobbles of the cosmos? With Einstein's time, perhaps, that abstraction outreaches itself, in a way, and collapses back onto us, onto the earth, onto the contingencies of here and there. Does that make sense?

PLG: You can tell that story of the earlier physics of time, as you suggest: Time passed from a world in which the sublunary sphere was thought of as corrupt and material to another realm, beyond the superlunary, to the inaccessible reaches of Newton's pure, mathematical time. The story of the late nineteenth century, though, is one in which the abstraction and concreteness of time are both present. Conventionalizing time through the exchange of signals forced the made-ness of time into the domain of the visible: time zones imprinted the technical fabrication of simultaneity in everyday life. Physicists, philosophers, psychologists, astronomers all were debating how to *make* time, how to measure it precisely and ship it from place to place. As Poincaré and Einstein inserted technical, engineered time into the physics of electrodynamics, they very deliberately set aside reference to Newtonian absolutes. They brought the abstract into the concrete not by jettisoning the realm of the ideas for the sun and seasons, but by joining the material to the abstract. We could say that the modernity of time is made visible by the absence of time-in-itself, by the absence of time-as-absolute.

DGB: In a way, that traditional history of time and timekeeping, particularly as cultivated by historians of science and technology, has been a story of the "demythologizing" of time. Sure, people went on using time imagery for didactic or symbolic functions from *vanitas* paintings of skulls to devotional hour glasses. But the history of time in science and technology has been the story of *abstracting* that pure and precisely metered flow from such accretions of "meaning." And yet, the products of such progressive purifications are always themselves reintegrated into the realm of human meaning making. For instance, the emerging concept of "geological time" in the eighteenth and nineteenth centuries rapidly came to be entangled with systematic theology and deist notions of natural law were rocks a particular lesson in eternity? This sort of endless "folding" between science and signification makes me wonder: Was there is there a didactic or symbolic significance in Einstein's time?

PLG: You might approach this in two ways. One would be to look at the specificity of the way Einstein and his physicist interlocutors treated time, and the other would be to explore how time was taken up in the wider cultural sphere. For example, Einstein was very amused by the "twin paradox" in which one twin travels out and back at relativistic speeds and ends up much younger than his stay-at-home sibling (he called this "the thing at its funniest"). But Einstein's heart was always elsewhere his real investment was in the *in*variants he found (for example, the absolute speed of light, or the identity of the laws of physics for all inertial reference frame observers). He was consistently more interested in these aspects of the theory than he was in the differing perspectives of each observer on space and time. But clearly the wider public was, and has remained, fascinated precisely with the relativity of time. From jokes to art and ethics, Einstein has been invoked to justify the tenet that the most basic of concepts were "just relative."

DGB: And yet and this is so easy for the lay reader to overlook "relativity" is predicated on a cosmic and universal *absolute*.

PLG: Indeed there is a great irony here since Einstein referred to his work as "Invariant Theory" until he could no longer buck the worldwide trend to label it "Relativity Theory."

DGB: So while the public seized on the relativity of time, what did physicists take from Einstein's intervention?

PLG: The critical gaze that Einstein cast on the notion of time promptly put other concepts under the microscope. Einstein had made time and simultaneity stand with, not behind, experience and procedure. Now physicists wanted to know how this rebuilding of a concept could be extended into quantum theory: What was causality? What did it mean for a particle to have a momentum and a position? Over the decades that followed, physical concepts fell one after another from a priori metaphysical heights to the ground where they (coupled to other concepts) met experimental inquiry. Time invariance that a movie of the physical world should be playable backwards and forwards was not, it seemed, the rule of a priori law. Nor was parity invariance (that the mirror reflection of phenomena should always be physically possible). Now from a distant philosophical perspective one might say that the criticism of causality, for example, was even more dramatic than Einstein's and Poincaré's critique of Newtonian absolute time. But the critique of time came first, and in a deep and abiding sense it guided the rebuilding of physical knowledge for generations after 1905. This, I believe, is because the reformation of time was not a change of doctrine ("time is better measured this way than that way"). At stake was what it meant to have a physical concept *at all*.

DGB: And at stake too was how one gains access to such a concept, no? Since "abstraction" or, as you call it, "sublimation" is not merely a way to tell historical stories; it is also a way to think about nature, it is a way to think about what science itself is and how it should be done. And yet Einstein's pursuit of time leads to a simultaneous apotheosis and inversion in the larger history of time in science and technology. His is an exercise in abstraction that is also, improbably, a kind of reification.

PLG: Understanding the history of time always involves examining exactly that relationship between the abstract and the concrete, and, for Einstein, understanding time itself demanded this as well. What I find so remarkable about the fin de siècle is that not just in relativity theory, but in the whole cultural surround, the categories of time and space exhibit a kind of abstract concreteness (or concrete abstraction). When the French finally persuaded the international community to "sanction" the meter in 1889, they held an elaborate ceremony, and a ritualized "burial" of the standard. At the moment the assembled dignitaries and scientists sealed the iridium-platinum rod in its triple-locked chamber (and shared out the keys), this precisely engineered rod rose to become "M" the object that could measure but not be measured. Practical? Of course; industrialists desperately needed a reference meter. But symbolic? How could one say no?

DGB: When people start playing with absolutes, when they start to conjure them they do, we do, the strangest things. It takes strange activity to bring absolutes into the contingencies and localities of human life. You can be sure that people are going to start making some very unusual gestures, and bring out keys and locks and boxes and bury things in the ground and make funny noises . . .

PLG: And particularly in the Third Republic, where religious iconology morphed into scientific-technical procedure. Time, too, was similarly concrete abstract. In the 1890s, for example, Poincaré joined a commission on the decimalization of time. On one reading, this was entirely a practical affair railroad administrators argued passionately for the simplicity that 9.56 or 22.34 o'clock would afford by allowing travelers to calculate time differences by simple subtraction. On another, though, it was entirely symbolic: a reanimation of the dream of rationality so passionately advocated during the French Revolution and brought to international prominence through the Convention of the Meter in the 1880s. Reflections on time are so often like this practical and more than practical, utterly utilitarian and highly symbolic.

PLG: Yes and no. True, they grasp time from the domain of the pure absolute. True, they rope it into procedure of electro-chronological coordination. But they surely do *not* sever time from its wide and deep bonds with modernity. Both scientists' writings on the "new mechanics" (with its non-absolute time) were widely read by artists, philosophers, and writers. Both though in different ways saw the relativity of time as a fundamental piece of the new physics.

DGB: The meaning of the clock would never be the same.

PLG: And yet, of course, clocks have never been just gears and pointers. Some were mounted in late medieval towers, establishing dominion of property and faith. In paintings they stood as harbingers of death. By the late nineteenth century, mounted in factories, observatories, and trading rooms, they stood for the modern ambitions of regulated life, precision-mapped territory, and the instantaneity of contemporary life. It is against this seven-hundred-year clock history that relativity entered, and when it did, there were certain to be no small effects.

DGB: "Grand narrative" historians have long talked about the conflict between "church time" and "merchant time" in the late-medieval period: the steeple clock versus the factory clock. On the one hand the time of God, on the other the time of labor and money. Your story of Einstein and Poincaré, of clocks and maps in the fin de siècle, could be read playfully, I admit as the final confrontation of these two chronometries of European civilization: in 1905 the Sensorium of God gets tied to the tracks of railway time...

PLG: But modernity is not or perhaps should I say "not just" a train wreck! Instead, what we see in this story is that the great metaphors of time trains and maps chosen by Einstein and Poincaré are both the most imaginative of all thought experiments, and, at the same time, the most everyday technologies of the modern world.

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1. The earth rotates once on its axis each day, or 360 degrees every 24 hours, or 15 degrees every hour. Longitude is measured with respect to some arbitrary zero line say, the meridian of Paris. So if we know that the sun is directly over our heads (it is noon where we are) and we get a telegraph message from Paris saying it was noon there an hour before, we know we are 15 degrees west of Paris.

This is the text of the essay, "Einstein, Poincaré & Modernity: a Conversation," by Peter L. Galison & D. Graham Burnett, which appeared in the journal Daedalus (Spring 2003) pp. 1-15.

***Peter L. Galison**'s book Einstein's Clocks, Poincaré's Maps (2003), forms the basis of this dialogue. A Fellow of the American Academy since 1992, Galison is the Mallinckrodt Professor of the History of Science and of Physics at Harvard University. Galison's other books, including* Image and Logic *(1997) and* How Experiments End *(1987), explore the interaction between the principal subcultures of twentieth-century physics experimentation, instrumentation, and theory and also the crosscurrents between physics and other fields.*

How Did Einstein Discover Relativity?

By John Stachel

This reprints an essay written ca. 1983, "'What Song the Syrens Sang': How Did Einstein Discover Special Relativity?" in John Stachel, Einstein from "B" to "Z".

If you have read Edgar Allen Poe's "The Murders in the Rue Morgue," perhaps you remember the epigraph that Poe chose for this pioneer detective story:

What song the Syrens sang, or what name Achilles assumed when he hid himself among women, though puzzling questions, are not beyond all conjecture.[1]

I believe that the problem of how Einstein discovered the special theory of relativity (SRT) falls into this category of "puzzling questions," that "are not beyond *all* conjecture."[2] Let me begin by explaining why.

When I started work on the Einstein Papers, there was already a large literature on the origins of SRT compared, say, to the rather scanty amount published on the origins of the general theory of relativity (GRT). So I assumed that the development of SRT must be fairly clear. However, I soon learned that the amount of work published on the origin of SRT and GRT are just about inversely proportional to the available primary source material. For GRT, we have a series of Einstein's papers from 1907 to 1915, capturing the successive steps of his search for the final version of the theory. In addition, there is extensive contemporary correspondence on the subject, several research notebooks, records of lectures given by Einstein during this period, not to mention a number of later reminiscences and historical remarks by Einstein.[3]

For SRT we have the paper *On the Electrodynamics of Moving Bodies*, in which the theory was first set forth in 1905 in its finished form, indeed a rather polished form (which is not to say that it bears no traces of its gestation process). The only earlier documentary evidence consists of literally a couple of sentences to be found in the handful of preserved early Einstein letters (I will quote both sentences later). We do have a number of later historical remarks by Einstein himself, sometimes transmitted by others (Wertheimer, Reiser-Kayser, Shankland, Ishiwara, for example), which raise many problems of authenticity and accuracy; and some very late Einstein letters, answering questions such as whether he had prior knowledge of the Michelson-Morley experiment, what works by Lorentz he had read, the influence of Poincaré, Mach, Hume, etc., on his ideas; Einstein's replies are not always self-consistent, it must be noted.[4]

Yet the urge to provide an answer to the question of the discovery of SRT has proven irresistible to many scholars. It is not hard to see why: A twenty-six year old patent expert (third class), largely self-taught in physics, who had never seen a theoretical physicist (as he later put it), let alone worked with one, author of several competent but not particularly distinguished papers, Einstein produced four extraordinary works in the year 1905, only one of which (not the relativity paper) seemed obviously related to his earlier papers. These works exerted the most profound influence on the development of physics in the 20th Century. How did Einstein do it? Small wonder that Tetu Hirosige, Gerald Holton, Arthur I. Miller, Abraham Pais, John Earman, Clark Glymour, Stanley Goldberg, Robert Rynasiewicz, Roberto Torretti, *et al*., have been moved to study this question. I shall not try to record my debts to and differences with each of these scholars, lest this survey become even longer and more tedious than it is already; but must at least acknowledge the influence of their work on my own.[5] I resisted the urge to conjecture for some years, but have finally succumbed, so I can well understand the temptation.

Contrary to my original, naive expectation, no general consensus has emerged from all this work. Given the nature of the available documentation and the difficulty of understanding any creative process-let alone that of a genius-this really is not surprising. I now believe that the most one can hope to do in discussing the discovery of SRT is to construct a plausible conjecture. Such a conjecture will be based upon a certain weighting of the scanty evidence we possess, based upon certain methodological hypotheses, as well as the imagination of the conjecturer.[6] There are bound to be differences of opinion in these matters. All one can demand is that it be made clear on what methodological hypotheses a conjecture is based, and a demonstration that the conjecture is in accord with the available evidence when the latter is weighted in accord with these hypotheses.

Let me emphasize that no such account can hope to encompass those elements of the creative process that Einstein referred to as "the irrational, the inconsistent, the droll, even the insane, which nature, inexhaustibly operative, implants into the individual, seemingly for her own amusement," for "These things are singled out only in the crucible of one's own mind." Yet one may draw courage for the type of conjecture I have in mind from another remark of Einstein:

"A new idea comes suddenly and in a rather intuitive way. That means it is not reached by conscious logical conclusions. But, thinking it through afterwards, you can always discover the reasons which have led you unconsciously to your guess and you will find a logical way to justify it. Intuition is nothing but the outcome of earlier intellectual experience."

I shall discuss only this intellectual, logical side of Einstein's struggles. Before trying to reconstruct these struggles, it is well to note that his outward existence was far from tranquil during the period when he was developing SRT. While attending the Polytechnic at Zurich, thanks to the support of maternal relatives, he was plagued by the thought that he was unable to help his family, which was in dire financial straits due to constant business reverses. He was the only graduate in his section (VIA) not to get an academic post, and lived a hand-to-mouth existence for almost two years, until he got a job at the Swiss Patent Office thanks to help from a friend's father. During this period he was under severe family pressure to break with his fiancee, whom he only married in 1903 after his father's death. His first child was born in 1904, and he had to support wife and child on his modest income from the Patent Office, while his mother found work as a housekeeper. So one must not think of Einstein as a tranquil academic, brooding at leisure on weighty intellectual problems. Rather one must imagine him fitting his intellectual work into the interstices of a professional career and personal life that might have overwhelmed someone with a different nature.

The main methodological hypothesis guiding my conjecture was stated by Hans Reichenbach some time ago: "...the logical schema of the theory of relativity corresponds surprisingly with the program which controlled its discovery." To put it in more hifalutin' terms, also due to Reichenbach, I believe that "the context of justification" of SRT used by Einstein can shed light on "the context of its discovery."[7] This hypothesis suggests that we can learn a good deal about the development of the theory by paying close attention to the logical structure of its initial presentation in 1905, and to the many accounts of the theory that Einstein gave afterwards. Of course, I have tried not to neglect any scrap of evidence known to me, including the pitifully small amount of contemporary documentation and the later reminiscences. But I have given special weight to Einstein's early papers, letters, and lectures, in which he sought to justify the theory to his contemporaries. Intellectually, Einstein was an exceedingly self-absorbed person, willing to go over and over the grounds for the theory again and again. These accounts, given over a number of years, are remarkably self-consistent. They provide evidence for a number of conjectures about the course of development of his own ideas, and occasionally even include explicit statements about it. I assume that by and large memory tends to deteriorate with time, and (worse) that pseudo "memories" tend to develop and even displace correct recollections. So, a second methodological hypothesis which I shall adopt is that, in case of discrepancies between such accounts, earlier ones are to be given greater weight than later ones. Explicit remarks that Einstein makes about the discovery of SRT in the course of his later expositions must always be given great weight, but the earlier he made them the greater the weight I give to them. Of course, if some feature of Einstein's accounts remains unchanged over many years, I take this as evidence for giving such a point the most weight.[8]

It follows from these methodological assumptions that I must preface my conjectures with a brief resume of the "logical schema of the theory of relativity" as it was first published in the 1905 paper. In this paper, as in almost all subsequent accounts, Einstein bases SRT on two fundamental principles: the principle of relativity and the principle of the constancy of the velocity of light. The principle of relativity originated in Galilean-Newtonian mechanics: Any frame of reference in which Newton's law of inertia holds (for some period of time) is now called an inertial frame of reference. From the laws of mechanics it follows that, if one such inertial frame exists, then an infinity of them must: All frames of reference (and only such frames) moving with constant velocity with respect to a given inertial frame are also inertial frames. All mechanical experiments and observations proved to be in accord with the (mechanical) principle of relativity: the laws of mechanics take the same form in any of these inertial frames. The principle of relativity, as Einstein stated it in 1905, asserts that *all* the laws of physics take the same form in any inertial frame-in particular, the laws of electricity, magnetism, and optics in addition to those of mechanics.

The second of Einstein's principles is based on an important consequence of Maxwell's laws of electricity, magnetism, and optics, as interpreted by H. A. Lorentz near the end of the nineteenth century. Maxwell had unified optics with electricity and magnetism in a single theory, in which light is just one type of electromagnetic wave. It was then believed that any wave must propagate through some mechanical medium. Since light waves easily propagate through the vacuum of interstellar space, it was assumed that any vacuum, though empty of ordinary, ponderable matter, was actually filled by such a medium, to which our senses did not respond: the ether. The question then arose, how does this medium behave when ordinary matter is present? In particular, is it dragged along by the motion of matter? Various possible answers were considered in the course of the nineteenth century, but finally only one view seemed compatible with (almost) all the known experimental results, that of H. A. Lorentz: The ether is present everywhere. Ordinary matter is made up of electrically charged particles, which can move through the ether, which is basically immobile. These charged particles, then called "electrons" or "ions", produce all electric and magnetic fields (including the electromagnetic waves we perceive as light), which are nothing but certain excited states of the immovable ether. The important experimental problem then arose of detecting the motion of ponderable matter-the earth in particular-through the ether.

No other theory came remotely close to Lorentz's in accounting for so many electromagnetic and especially optical phenomena. This is not just my view of Lorentz's theory, it was Einstein's view. In particular, he again and again cites the abberration of starlight and the results of Fizeau's experiment on the velocity of light in flowing water as *decisive* evidence in favor of Lorentz's interpretation of Maxwell's equations.

A direct consequence of Lorentz's conception of the stationary ether is that the velocity of light with respect to the ether is a constant, independent of the motion of the source of light (or its frequency, amplitude, or direction of propagation in the ether, etc.).

Einstein adopted a slightly-but crucially-modified version of this conclusion as his second principle: There is an *inertial frame* in which the speed of light is a constant, independent of the velocity of its source. A Lorentzian ether theorist could agree at once to this statement, since it was always tacitly assumed that the ether rest frame is an inertial frame of reference and Einstein had "only" substituted "inertial frame" for "ether." But Einstein's omission of the ether was deliberate and crucial: by the time he formulated SRT he did not believe in its existence. For Einstein a principle was just that: a principle-a starting point for a process of deduction, not a deduction from any (ether) theory. (I am here getting ahead of my story and will return to this point later.) The Lorentzian ether theorist would add that there can only be *one* inertial frame in which the light principle holds. If the speed of light is a constant in the ether frame, it must be non-constant in every other inertial frame, as follows from the (Newtonian) law of addition of velocities. The light principle hence *seems* to be incompatible with the relativity principle. For, according to the relativity principle, *all* the laws of physics must be the same in any inertial frame. So, if the speed of light is constant in one inertial frame, and that frame is not physically singled out by being the rest frame of some medium (the ether), then the speed of light *must* be the same (universal) constant in every other inertial frame (otherwise the democracy of inertial frames is violated). As Einstein put it in 1905, his two principles are "apparently incompatible." Of course, if they really were incompatible logically or physically, that would be the end of SRT.[9]

Einstein showed that they are not only logically compatible, but compatible with the results of all optical and other experiments performed up to 1905 (and since, we may add). He was able to show their logical compatibility by an analysis of the concepts of time, simultaneity, and length, which demonstrated that the speed of light really could have the privileged status, implied by his two principles, of being a universal speed, the same in every inertial frame of reference.[10]

Now I shall begin my conjecture about Einstein's discovery of SRT. In a 1921 lecture, Einstein stated that SRT originated from his interest in the problem of the optics of moving bodies. He seems to have been fascinated from an early age by the nature of light, a fascination that persisted throughout his life. From an essay he wrote in 1895, (at age 16), we know that he then believed in the ether, and had heard of Hertz's experiments on the propagation of electromagnetic waves; but he does not show any knowledge of Maxwell's theory. In much later reminiscences, he reports that during the following year (1895-1896) he conceived of a thought experiment: what would happen if an observer tried to chase a light wave? Could s/he catch up with it? If so, s/he ought to see a non-moving light wave form, which somehow seemed strange to him. In retrospect, he called this "the first childish thought-experiment that was related to the special theory of relativity." Reliable accounts inform us that during his second year (1897-98) at the Swiss Federal Technical Institute, or Poly as it was then called, he tried to design an experiment to measure the velocity of the earth through the ether, being then unacquainted with either the theoretical work on this problem by Lorentz or the experiment of Michelson and Morley (M-M). A precious bit of contemporary documentary evidence reinforces this later account. In a letter to his schoolmate and friend Marcel Grossmann, written in the summer of 1901 (by then both had graduated from the Poly), Einstein wrote:

A considerably simpler method for the investigation of the relative motion of matter with respect to the light ether has again occurred to me, which is based on ordinary interference experiments. If only inexorable destiny gives me the time and peace necessary to carry it out.

At first sight, it would seem remarkable for Einstein to have written these words (which also show that he had not yet abandoned the concept of the ether), if he knew about the M-M experiment at this time.

However, while still at the Poly (i.e., before 1901) he appears to have studied Maxwell's theory (not covered in his school lectures) on his own, perhaps from the new textbook of August Föppl (which, in various reincarnations, such as Föppl-Abraham, Abraham-Becker, Becker-Sauter, has stayed in print to this day). Föppl discusses a problem which evidently made a strong and lasting impression on Einstein, since he opens the 1905 paper with a discussion of it. This is the problem of the relative motion of a magnet and a conducting wire loop. If the loop is at rest in the ether and the magnet is moved with a given velocity, a certain electric current is induced in the loop. If the magnet is at rest, and the loop moves with the *same* relative velocity, a current of the same magnitude and direction is induced in the loop. However, the ether theory gives a different explanation for the origin of this current in the two cases. In the first case an electric field is supposed to be created in the ether by the motion of the magnet relative to it (Faraday's law of induction). In the second case, no such electric field is supposed to be present since the magnet is at rest in the ether, but the current results from the motion of the loop through the magnetic field (Lorentz force law). This asymmetry of explanation, not reflected in any difference in the phenomena observed, must already have been troubling to Einstein. Even more troubling was the knowledge, when he acquired it, that all attempts to detect the motion of ponderable matter through the ether had failed. This was an "intolerable" (his word, about 1920) situation. Observable electromagnetic phenomena depend only on the *relative* motions of ponderable matter; their explanations differ, however, depending on the presumed state of motion of that matter relative to the hypothetical ether; yet all attempts to detect this presumed motion of ordinary matter relative to the ether end in failure! He later (c. 1920) recalled that the phenomenon of electromagnetic induction compelled him to adopt the relativity principle.

In 1938 he wrote "The empirically suggested non-existence of such an [ether wind] is the main starting point [point of departure] for the special theory of relativity."[11] It is not clear when the significance of the failure of all attempts to detect the motion of ordinary matter through the ether first struck him. The letter quoted above suggests that it was after the summer of 1901. We know from a letter to another friend, Michele Besso, dating from early 1903, that he had decided to "carry out comprehensive studies in electron theory." No later than that, and quite possibly earlier, he read Lorentz's 1895 book, "Attempt at a Theory of Electrical and Optical Phenomena in Moving Bodies." Einstein surely learned about, the many such failures by reading this book, since one of its main purposes was to show that such failures were compatible with Lorentz's stationary ether theory. His later comments suggest that study of this book (Einstein says this is the only work by Lorentz he read before 1905) convinced him of the essential superiority of Lorentz' approach to the optics of moving bodies; yet it also convinced him that the Lorentz theory was still not fully satisfactory. Lorentz could explain away the failure to detect motion of matter relative to the ether convincingly to Einstein in all cases but one: the M-M experiment. To explain this, Lorentz had to introduce a special hypothesis, which to Einstein seemed completely unconnected with the rest of the theory: the famous Lorentz contraction. To Einstein, such an approach was not a satisfactory way out of the "intolerable dilemma." It seemed preferable to him to accept at face value the failure of the M-M and all similar experiments to detect motion of matter relative to the ether. Taken by themselves, these negative results suggested to Einstein that the relativity principle applied to electromagnetism, while the ether should be dropped as superfluous. There has been some confusion on this important point, so I shall expand on it. Sometimes the case is presented in such a way as to suggest that it was the "philosophical concept" of the relativity of all motion, as Einstein once called it, which was the key step in his rejection of the ether. But the concept of a stationary ether, as well as of a moving ether, is quite compatible with this philosophical concept of the relativity of motion: one need only assume that motions relative to the ether in the first case, as well as relative motions of the parts of the ether in the second, have physical efficacy. The leading advocates of both the dragged-along and the immovable ether concepts, Hertz and Lorentz, respectively, both understood this and both were read by Einstein.[12]

By the time he gave up the ether concept, Einstein most likely took this philosophical conception of the relativity of all motion for granted, presumably under the influence of his early reading of Mach's *Mechanics* (around 1897). What bothered him now was that no phenomenon existed that could be interpreted as empirical evidence for the physical efficacy of the motion of ordinary matter relative to the ether, in spite of repeated efforts to find one. Yet the best available theory- Lorentz's theory-could only attempt to explain away such failures. These explanations were satisfactory, within the framework of Lorentz' theory, in almost all known cases (i.e., for all experiments sensitive only to order v/c), and Einstein even seems to have been tempted to give up what we may call his physical relativity principle (with no ether needed). But Lorentz's explanation of the M-M experiment seemed to Einstein so artificial that he resisted this temptation, opting for the physical relativity principle. After eliminating the ether from the story altogether, one can simply take the results of the M-M and similar experiments as empirical evidence for the equivalence of all inertial frames for the laws of electricity, magnetism and optics as well as those of mechanics. I believe Einstein gave up the ether concept and definitely opted for the physical relativity principle at least a couple of years before the final formulation of SRT, perhaps even earlier. At any rate, at some point well before the 1905 formulation of the theory, he made this choice and adhered to it thereafter.

There was a related motive for his skepticism with regard to the ether, which I shall now mention. Not only was Einstein working on problems of the optics of moving bodies, he was also working on problems related to the emission and absorption of light by matter and of the equilibrium behavior of electromagnetic radiation confined in a cavity-the so-called black body radiation problem. He was using Maxwell's and Boltzmann's statistical methods, which he had redeveloped and refined in several earlier papers, to analyze this problem. This was itself a daring step, since these methods had been developed to help understand the behavior of ordinary matter while Einstein was applying them to the apparently quite different field of electromagnetic radiation.[13] The "revolutionary" conclusion to which he came was that, in certain respects, electromagnetic radiation behaved more like a collection of particles than like a wave. He announced this result in a paper published in 1905, three months before his SRT paper. The idea that a light beam consisted of a stream of particles had been espoused by Newton and maintained its popularity into the middle of the 19th century. It was called the "emission theory" of light, a phrase I shall use. The need to explain the phenomena of interference, diffraction and polarization of light gradually led physicists to abandon the emission theory in favor of the competing wave theory, previously its less-favored rival. Maxwell's explanation of light as a type of electromagnetic wave seemed to end the controversy with a definitive victory of the wave theory. However, if Einstein was right (as events slowly proved he was) the story must be much more complicated. Einstein was aware of the difficulties with Maxwell's theory-and of the need for what we now call a quantum theory of electromagnetic radiation-well before publishing his SRT paper. He regarded Maxwell's equations as some sort of statistical average-of what he did not know, of course-which worked very well to explain many optical phenomena, but could not be used to explain all the interactions of light and matter. A notable feature of his first light quantum paper is that it almost completely avoids mention of the ether, even in discussing Maxwell's theory. Giving up the ether concept allowed Einstein to envisage the possibility that a beam of light was "an independent structure," as he put it a few years later, "which is radiated by the light source, just as in Newton's emission theory of light."

So abandonment of the concept of the ether was a most important act of liberation for Einstein's thought in two respects: It allowed Einstein to speculate more boldly on the nature of light and it opened the way for adoption of his relativity principle as a fundamental criterion for all physical laws. I must add a word about Einstein's use of such principles as a guide to further research. In 1919 he explicitly formulated a broad distinction between constructive theories and theories of principle. Constructive theories attempt to explain some limited group of phenomena by means of some model, some set of postulated theoretical entities. For example, many aspects of the behavior of a gas could be explained by assuming that it was composed of an immense number of constantly colliding molecules. Theories of principle formulate broad regularities, presumably obeyed by all physical phenomena, making these principles criteria ("rules of the game") that any constructive theory must satisfy. For example, the principles of thermodynamics are presumed to govern all macroscopic phenomena. They say nothing about the, micro-structure or detailed behavior of any particular gas, but do constitute limitations on any acceptable constructive theory of such a gas. Any theory not conserving the energy of the gas, for example, would be immediately rejected. Since the turn of the century, Einstein had been searching for a constructive theory of light, capable of explaining all of its properties on the basis of some model, and was to continue the search to the end of his days. But, "Despair[ing] of the possibility of discovering the true answer by constructive efforts," as he later put it, he decided that the only possible way of making progress in the absence of such a constructive theory was to find some set of principles that could serve to limit and guide the search for a constructive theory.[14] There is no contemporary evidence showing when Einstein adopted this point of view (he first indicated it in print as early as 1907). I believe he had done so by 1905. The structure of the 1905 SRT paper is certainly compatible with his having done so. It is based on the statement of two such principles, deduction of various kinematic consequences from them, and their application to Maxwell's electrical and optical theory.

To return to the main thread of my conjecture, I believe that Einstein dropped the ether hypothesis and adopted his relativity principle by 1903 or 1904 at the latest. This is by no means the end of the story. It seemed that he must then drop Lorentz's version of Maxwell's theory, based as it was on the ether hypothesis. With what was he to replace it? There is good evidence suggesting he spent a great deal of effort trying to replace it with an emission theory of light-the sort of theory suggested by his concurrent researches into the quantum nature of light.[15] An emission theory is perfectly compatible with the relativity principle. Thus, the M-M experiment presented no problem; nor is stellar abberration difficult to explain on this basis.[16]

Einstein seems to have wrestled with the problems of an emission theory of light for some time, looking for a set of differential equations describing such a theory that could replace the Maxwell-Lorentz equations; and trying to explain a number of optical experiments, notably the Fizeau experiment, based on some version of the emission theory. He could not find any such equations, and his attempt to explain the Fizeau experiment led him to more and more bizarre assumptions to avoid an outright contradiction. So he more-or-less abandoned this approach (you will soon see why I say more-or-less), after perhaps a year or more of effort, and returned to a reconsideration of the Maxwell-Lorentz equations. Perhaps there was a way of making these equations compatible with the relativity principle once one abandoned Lorentz's interpretation via the ether concept.

But here he ran into the most blatant-seeming contradiction, which I mentioned earlier when first discussing the two principles. As noted then, the Maxwell-Lorentz equations imply that there exists (at least) one inertial frame in which the speed of light is a constant regardless of the motion of the light source. Einstein's version of the relativity principle (minus the ether) requires that, if this is true for one inertial frame, it must be true for all inertial frames. But this seems to be nonsense. How can it happen that the speed of light relative to an observer cannot be increased or decreased if that observer moves towards or away from a light beam? Einstein states that he wrestled with this problem over a lengthy period of time, to the point of despair. We have no details of this struggle, unfortunately.

Finally, after a day spent wrestling once more with the problem in the company of his friend and patent office colleague Michele Besso, the only person thanked in the 1905 SRT paper, there came a moment of crucial insight. In all of his struggles with the emission theory as well as with Lorentz's theory, he had been assuming that the ordinary Newtonian law of addition of velocities was unproblematic. It is this law of addition of velocities that allows one to "prove" that, if the velocity of light is constant with respect to one inertial frame, it cannot be constant with respect to any other inertial frame moving with respect to the first. It suddenly dawned on Einstein that this "obvious" law was based on certain assumptions about the nature of time always tacitly made. In particular, the concept of the velocity of an object with respect to an inertial frame depends on time readings made at two different places in that inertial frame. (He later referred to this moment of illumination as "the step.")[17]

How do we know that time readings at two such distant places are properly correlated? Ultimately this boils down to the question: how do we decide when events at two different places in the same frame of reference occur at the same time, i.e., simultaneously? Isn't universal simultaneity an intuitively obvious property of time? Here, I believe, Einstein was really helped by his philosophical readings. He undoubtedly got some help from his readings of Mach and Poincaré, but we know that he was engaged in a careful reading of Hume at about this time; and his later reminiscences attribute great significance to his reading of Hume's *Treatise on Human Nature*. What could he have gotten from Hume? I think it was a relational-as opposed to an absolute-concept of time and space. This is the view that time and space are not to be regarded as self-subsistent entities; rather one should speak of the temporal and spatial aspects of physical processes; "The doctrine," as Hume puts it, "that time is nothing but the manner, in which some real object exists." I believe the adoption of such a relational concept of time was a crucial step in freeing Einstein's outlook, enabling him to consider critically the tacit assumptions about time going into the usual arguments for the "obvious" velocity addition law. This was the second great moment of liberation of his thought.

I shall not rehearse Einstein's arguments here, but it led to the radically novel idea that, once one physically defines simultaneity of two distant events relative to one inertial frame of reference, it by no means follows that these two events will be simultaneous when the *same* definition is used relative to another inertial frame moving with respect to the first. It is not logically excluded that they *are* simultaneous relative to all inertial frames. If we make that assumption, we are led back to Newtonian kinematics and the usual velocity addition law, which is logically quite consistent. However, if we adopt the two Einstein principles, then we are led to a new kinematics of time and space, in which the velocity of light is a universal constant, while simultaneity is different with respect to different inertial frames; this is also logically quite consistent. The usual velocity addition law is then replaced by a new one, in which the velocity of light "added" to any other velocity ("added" in a new sense-it would be better to say "compounded with") does not increase, but stays the same! The Maxwell-Lorentz equations, when examined with the aid of this new kinematics, prove to take the same form in every inertial frame. They are, therefore, quite compatible with the relativity principle, which demands that the laws of electricity, magnetism and optics have this property. The presence or absence of an electric or magnetic field, is then also found to be relative to an inertial frame, allowing a completely satisfactory relativistic analysis of the example of the conducting wire loop and magnet in relative motion. Within six weeks of taking "the step," Einstein later recalled, he had worked out all of these consequences and submitted the 1905 SRT paper to *Annalen der Physik*.

This does not imply that Lorentz's equations are adequate to explain all the features of light, of course. Einstein already knew they did not always correctly do so-in particular in the processes of its emission, absorption and its behavior in black body radiation. Indeed, his new velocity addition law is also compatible with an *emission* theory of light, just *because* the speed of light compounded with any lesser velocity still yields the same value. If we model a beam of light as a stream of particles, the two principles can still be obeyed. A few years later (1909), Einstein first publicly expressed the view that an adequate future theory of light would have to be some sort of fusion of the wave and emission theories. This is an example of how the special theory of relativity functioned as a theory of principle, limiting but not fixing the choice of a constructive theory of light.

Here I shall end my conjectures on how Einstein arrived at SRT. To briefly recapitulate, I believe that the first principle, the relativity principle, recapitulates his struggles with the mechanical ether concept which led finally to the first crucial liberation of his thought-the abandonment of the ether. The second principle, the principle of the constancy of the speed of light, recapitulates his struggle, once he had definitely opted for the relativity principle, first to evade the Maxwell-Lorentz theory by an emission theory; then to isolate what was still valid in the Maxwell Lorentz theory after giving up the ether concept and abandoning absolute faith in the wave theory of light. The struggle to reconcile the two principles could only end successfully after the second great liberation of his thought: the relativisation of the concept of time. The resulting theory did not force him to choose between wave and emission theories of light, but rather led him to look forward to a synthesis of the two. This synthesis was finally achieved, over twenty years later, in the quantum theory of fields, to the satisfaction of most physicists, but ironically, never to that of Einstein.

I cannot ask you to accept my conjectures after all of my warnings at the outset of this paper, but will be content if you say "Si non è vero, è ben trovato," "If it isn't true, it's well contrived."

Notes

1. Poe is quoting Sir Thomas Browne's *Hydrotaphia*. BACK

2. A preliminary question is raised by my use of the word "discovery." Is it better to speak of the "discovery" or the "creation" of a theory like SRT? "Discovery" suggests the finding of some pre-existent, objective structure, as when we say "Columbus discovered America." "Creation" suggests an individual, subjective act, as when we say "Tolstoy created *Anne Karenina*." Neither word seems really appropriate to describe what goes on in the scientific endeavor. Einstein apparently preferred the word "Erfindung" (invention) to describe how scientific theories come into being. Speaking of Mach, Einstein says: "Er meinte gewissermassen, dass Theorien durch *Entdeckung* und nicht durch *Erfindung* entstehen." (*Einstein-Besso Correspondence* (Hermann, Paris 1972), p. 191, dated January 6, 1948. BACK

3. In the study of the discovery of GRT, therefore, one may hope to formulate conjectures which can be either confirmed or refuted. For example: A study of Einstein's published papers and private correspondence between 1912-1915 convinced me that the standard explanation for his failure to arrive at the correct gravitational field equations until the end of this period-namely, his presumed lack of understanding of the meaning of freedom of coordinate transformations in a generally covariant theory and the ability to impose coordinate conditions that this freedom implied-could not be correct (see "Einstein's Search for General Covariance, 1912-1915," presented at the Ninth International Conference on General Relativity and Gravitation, July 17, 1980, in Stachel *Einstein from "B" to "Z"*, pp. 301338). On the basis of his study of a research notebook of Einstein from the early part of this period, John Norton was able to prove that Einstein already was aware of the possibility of imposing coordinate conditions on a set of field equations, and indeed had used the harmonic coordinate conditions (see John Norton, "How Einstein found his field equations: 1912-1915," *Historical Studies in the Physical Sciences 14*, 253 (1984). For reasons discussed in the text, one cannot hope to confirm or disconfirm most conjectures about the origins of SRT.BACK

4. For a survey of this material for the period up to 1923, see J. Stachel, "Einstein and Michelson: The Context of Discovery and the Context of Justification," Astron. Nachricht. **303**, 47 (1982). Unless otherwise noted, quotations from Einstein are cited from this paper, which gives the full references. [See Stachel, *Einstein from "B" to* "Z", pp. 177-190].BACK

5. See Arthur I. Miller, *Albert Einstein's Special Theory of Relativity* (Addison-Wesley, Reading 1981), which contains references to his earlier papers as well as those of Holton, Hirosige and many others; Abraham Pais, 'Subtle is the Lord. . .' *The Science end the Life of Albert Einstein* (Oxford U.P., New York 1982); Stanley Goldberg, *Understanding Relativity* (Birkhauser, Boston 1984); Roberto Torretti, *Relativity end Geometry* (Pergamon, Oxford 1983). Earman, Glymour and Rynasiewicz have not yet published a full account of their views; I thank them for making available copies of several preprints on this subject. BACK

6. A popular epigram among historians runs: "God is omnipotent, but even He cannot change the past. That is why He created historians." BACK

7.See the reference in footnote 4 for the source of the citations from Reichenbach. If my thesis here is correct, this argues against the still widely held view that these two contexts should be rigorously separated. But in this paper I shall not elaborate on the wider issue. BACK

8. For example, Einstein's statements of the second principle of SRT, the light principle, remained remarkably consistent throughout his lifetime (see the discussion of this principle below). Indeed, an apparent exception in the printed text of his article "What is the Theory of Relativity?," published originally in English translation in the *Times* of London in 1919, proved to be based upon an incorrect transcription of his manuscript. BACK

9. Much of the anti-relativity literature, which still continues to grow in volume if not in weight, is based on attempts to show that the two principles are indeed logically incompatible. BACK

10. Sometimes (e.g., by Pais and Goldberg), this consequence of Einstein's two principles is asserted to be his second principle. This is incorrect factually (Einstein's account of the second principle is one of the most consistent features of his discussions of SRT over the years-see footnote 8), and disturbing for several reasons: a) it makes it impossible to explain why Einstein refers to the two principles as apparently contradictory. There is no contradiction apparent between the relativity principle and this deduction from it; b) it is logically defective, since the two principles would no longer be logically independent, as they are in Einstein's formulation; c) most important for present purposes, this formulation deprives us of important clues to Einstein's reasoning that led to the development of SRT. BACK

11. Einstein to Max Talmey, June 6, 1938. The German text reads: "Die empirisch suggerierte Nichtexistenz einer solchen bevorzugten 'Wind-Richtung' ist der Haupt-Ausgangspunkt der speziellen Relativitatstheorie." BACK

12. Hertz said: "... the absolute motion of a rigid system of bodies has no effect upon any internal electromagnetic processes whatever in it, provided that all the bodies under consideration, including the ether as well, actually share the motion." (*Electromagnetic Waves*, p. 246). Lorentz said:

That one cannot speak of the absolute rest of the ether, is self-evident indeed; the expression wouldn't even have any meaning. If I say for short, the ether is at rest, this only means that one part of this medium is not displaced with respect to the others and that all perceptible movements of the heavenly bodies are relative movements with respect to the ether. [*Versuch*, p. 4 (1895).] BACK

13. He was not alone in transferring statistical methods from ordinary matter to radiation. Planck had already done so, but Einstein did not see the relation of his work to Planck's until after publishing his first paper on the subject. BACK

14. See Albert Einstein, *Autobiographical Notes* (Open Court, LaSalle 1979), pp. 48 (German text) and 49 (English translation). BACK

15. One such piece of evidence, not cited in my earlier paper (see footnote 4), has only recently come to light. It occurs in the most complete review of SRT that Einstein ever wrote. It was prepared in 1912 but never published, and is still in private hands. Luckily, a copy has come into the possession of the Einstein Archive. In it, Einstein explains at some length the difficulties that are encountered (and presumably these are the ones he had encountered), if one tries to explain the results of the Fizeau experiment on the basis of an emission theory of light combined with the relativity principle and Galilei-Newtonian kinematics. [See The *Collected Papers of Albert Einstein*, vol. 4. *The Swiss Years: Writings 1912-1914* (Princeton University Press, Princeton 1995), Doc. 1, "Manuscript on the Special Theory of Relativity," pp. 32-36]. BACK

16. Indeed, the earliest explanation of stellar abberation had been based on the emission theory. BACK

17. Abraham Pais has mentioned this in describing his conversations with Einstein. BACK

This is the text of "'What Song the Syrens Sang': How Did Einstein Discover Special Relativity?" as printed in John Stachel, *Einstein from "B" to "Z"* (Boston : Birkhäuser, 2002), pp. 157-169. It is an English text of "Quale canzone cantarono le sirene: come scopro Einstein la teoria speciale della relatività?" published in *L'Opera di Einstein* (1989), pp. 21-37.

John Stachel *is Professor of Physics Emeritus and Director of the Center of Einstein Studies at Boston University. He has written a variety of articles on aspects of the history of both special and general relativity and other topics, and has edited or co-edited a number of books dealing with Einstein and relativity.*

Einstein on the Photoelectric Effect

By David Cassidy

Adapted from David Cassidy's book, Einstein and Our World.

Light and other electromagnetic radiation, such as radio waves, are obviously waves—or so everyone thought. Maxwell and Lorentz had firmly established the wave nature of electromagnetic radiation in electromagnetic theory. Numerous experiments on the interference, diffraction, and scattering of light had confirmed it. We can well appreciate the shock and disbelief when Einstein argued in 1905 that under certain circumstances light behaves not as continuous waves but as discontinuous, individual particles. These particles, or "light quanta," each carried a "quantum," or fixed amount, of energy, much as automobiles produced by an assembly plant arrive only as individual, identical cars—never as fractions of a car. The total energy of the light beam (or the total output of an assembly plant) is the sum total of the individual energies of these discrete "light quanta" (or automobiles), what are called today "photons." Theories of matter and electromagnetic radiation in which the total energy is treated as "quantized" are known as quantum theories. Although Einstein was not the first to break the energy of light into packets, he was the first to take this seriously and to realize the full implications of doing so.[1]

Like the special theory of relativity, Einstein's quantum hypothesis arose from an experimental puzzle and an asymmetry or duality in physical theories. The duality consisted of the well-known distinction between material atoms and continuous ether, or, as Einstein wrote in the opening sentence of his light quantum paper, "between the theoretical conceptions that physicists have formed about gases and other ponderable bodies and the Maxwell theory of electromagnetic processes in so-called empty space." [2] As noted earlier, Boltzmann and others conceived of gases as consisting of myriads of individual atoms, while Maxwell and Lorentz envisioned electromagnetic processes as consisting of continuous waves. Einstein sought a unification of these two viewpoints by removing the asymmetry in favor of a discontinuous, "atomic," or quantum, theory of light. Resolution of an experimental puzzle encouraged this approach.

The puzzle concerned so-called blackbody radiation, that is, the electro-magnetic radiation given off by a hot, glowing coal in a fireplace, or the radiation emerging from a small hole in a perfectly black box containing electromagnetic radiation at a high temperature. Scientists at the German bureau of standards in Berlin, who were interested in setting standards for the emerging electric lighting industry in Germany, had measured the distribution of the total electromagnetic energy in a black box—which would also apply to a glowing light bulb—among the different wavelengths of the light. But no one until Max Planck, at the turn of the century, was able to give a single mathematical formula for the observed distribution of the energy among the emitted wavelengths. Starting with the Maxwell-Lorentz theory of radiation and some natural assumptions about energy, Planck hoped to derive this formula from the second law of thermodynamics. Planck failed to attain the observed formula on these assumptions. Even Lorentz had to admit that his own electron theory could not account for blackbody radiation.

Only by reluctantly introducing a radical new assumption into his mathematics could Planck attain the correct formula. The assumption was that the energy of the radiation does not act continuously, as one would expect for waves, but exerts itself in equal discontinuous parcels, or "quanta," of energy. In essence Planck had discovered the quantum structure of electromagnetic radiation. But Planck himself did not see it that way; he saw the new assumption merely as a mathematical trick to obtain the right answer. Its significance remained for him a mystery. Thomas Kuhn has argued that it is not to Planck in 1900 but to Einstein in 1905 that we owe the origins of quantum theory.[3]

Encouraged by his brief but successful application of statistical mechanics to radiation in 1904, in 1905 Einstein attempted to resolve the duality of atoms and waves by demonstrating that part of Planck's formula can arise only from the hypothesis that electromagnetic radiation behaves as if it actually consists of individual "quanta" of energy. The continuous waves of Maxwell's equations, which had been confirmed experimentally, could be considered only averages over myriads of tiny light quanta, essentially "atoms" of light.[4]

With his light quantum hypothesis Einstein could not only derive part of Planck's formula but also account directly for certain hitherto inexplicable phenomena. Foremost among them was the photoelectric effect: the ejection of electrons from a metal when irradiated by light. The wave theory of light could not yield a satisfactory account of this, since the energy of a wave is spread over its entire surface. Light quanta, on the other hand, acting like little particles, could easily eject electrons, since the electron absorbs the entire quantum of energy on impact.

At first Einstein believed that the light-quantum hypothesis was merely "heuristic": light behaved only as if it consisted of discontinuous quanta. But in a brilliant series of subsequent papers in 1906 and 1907, Einstein used his statistical mechanics to demonstrate that when light interacts with matter, Planck's entire formula can arise only from the existence of light quanta—not from waves. Einstein considered that light quanta, together with the equivalence of mass and energy, might result in a reduction of electrodynamics to an atom-based mechanics. But in 1907 he
discovered that atoms in matter are also subject to a quantum effect.[5]

Here he made use of another galling experimental problem. Experimentalists had found that when solid bodies were cooled, the amount of heat they lost failed to fit a simple formula that followed from Newtonian mechanics. Einstein showed that the experiments could be explained only on the assumption that the oscillating atoms of the solid lattice can have only certain, specific energies, and nothing in between. In other words, even the motions of atoms—which are continuous in Newtonian mechanics—exhibit a quantum structure. Mechanics and electrodynamics both required radical revision, Einstein now concluded: neither could yet account for the existence of electrons or energy quanta.[6]

Notes

1. Thomas S. Kuhn, *Black-Body Theory and the Quantum Discontinuity, 1984-1912* (1978). BACK

2. Kuhn, *Black-Body Theory*; Martin J. Klein, "Einstein's First Paper on Quanta," *Natural Philosopher* **2** (1963): 59-86; Max Jammer, *The Conceptual Development of Quantum Mechanics* (1966). Quote: Albert Einstein, *The Collected Papers of Albert Einstein*, ed. John Stachel et al. (1987-), vol. 2, 150. BACK

3. Kuhn, *Black-Body Theory*; Martin J. Klein, "Max Planck and the Beginnings of the Quantum Theory," *Archive for History of Exact Sciences* **1** (1962): 459-79. BACK

4. Klein, "Einstein's First Paper"; Kuhn, *Black-Body Theory*. BACK

5. Kuhn, *Black-Body Theory*; Einstein, *Collected Papers,* vol. 2, 134-48. BACK

6. Martin J. Klein, "Einstein, Specific Heats, and the Early Quantum Theory," *Science* **148** (1965): 173-80. BACK

This text is adapted from David Cassidy, *Einstein and Our World* (Humanities Press, 1995, reissued Amherst, NY: Humanity Books, 1998).

David Cassidy *is Professor of Natural Sciences at Hofstra University. He has served as an editor of the Einstein Papers and is author of a number of works in history of physics including* Uncertainty: The Life and Science of Werner Heisenberg *(1991) and a related Web exhibit,* Heisenberg/Uncertainty.

Einstein on Brownian Motion
By David Cassidy

Adapted from David Cassidy's book, Einstein and Our World.

The Challenge of Heat

At the turn of the century Einstein, by holding to the nineteenth-century ideal of unifying physics on the foundation of mechanics, was in a dwindling minority. Most other theoretical physicists sought unity in one of two nonmechanical alternatives: the so-called energetic and electromagnetic points of view. These alternatives arose from nineteenth-century challenges to the mechanical program in studies of heat and electromagnetism. It was in an effort to reform mechanics and electrodynamics in the wake of these developments that Einstein produced his 1905 works.

The study of the dynamics of heat flow, or thermodynamics, had culminated in two fundamental laws regarding heat. The first law related heat, energy, and useful work to each other in thermal processes. This law could be understood in terms of the motions and collisions of Newtonian atoms. The second law could not. According to the second law, the flowing of heat in natural processes, such as the melting of an ice cube, is always irreversible; that is, heat will not naturally flow of its own accord in the opposite direction—the melted cube at room temperature will not refreeze by itself. How to account for this in mechanical terms?

If, as Newton and others had suggested, all matter consists of atoms (or molecules), then heat is nothing but the energy of motion, or kinetic energy, of the atoms. But, like so many bouncing marbles or billiard balls, all atoms in their microscopic interactions must obey Newtonian mechanics. Those interactions are reversible: a motion picture of a collision between simple atoms will look perfectly normal if it is run backwards in time. So how does the irreversibility of macroscopic events, such as melting ice cubes, arise?

This and other paradoxes encouraged those who, like Ernst Mach, chose to deny the very existence of material atoms. One group, led by physical chemist Wilhelm Ostwald, seeing their chance in paradox, rejected the entire mechanical program, holding the laws of thermodynamics, not mechanics, as fundamental."[1] Mechanics required hypotheses about matter and invisible atoms in motion, but thermodynamics referred only to energy and its observed transformations in the everyday world. Because thermodynamic laws were closer to laboratory observations, universal, freed of paradox, and independent of matter, Ostwald and his followers proclaimed the predominance of a new "energetic" worldview: energy and the laws of thermodynamics are the bases for understanding all processes within physical science, and even beyond. Upholders of this view, known as "energeticists," though unable to make much of their position, maintained it even into the depths of World War 1, which they condemned as an enormous waste of energy (to say little of human lives).

Others, of course, held tightly to material atoms. They found support in the work of Maxwell, Rudolf Clausius, and Ludwig Boltzmann, who managed to resolve the reversibility paradox in favor of atoms. The second law of thermodynamics says that most natural processes are irreversible, in contradiction to the Newtonian mechanics of atoms. Boltzmann in particular resolved this contradiction by interpreting the second law as a new type of law: a statistical, not an absolute, law. Since there are so many atoms or molecules, even in a tiny ice cube, it is extremely unlikely—but not impossible—for the myriads of molecules in a melted cube to return in a finite time from the disorder of a liquid to their original orderly, crystalline arrangement. The macroscopic properties of heat and material objects, such as irreversibility, arise from the statistical behavior of numerous mechanical atoms, a behavior to be described by a new "statistical mechanics."

Boltzmann and the American physicist J. Willard Gibbs provided the first accounts of how exactly the second law of thermodynamics arises from the statistical behavior of myriads of randomly moving atoms, Unaware of these writings, Einstein devoted three brilliant early papers during the years 1902 to 1904 to an independent derivation of the second law in the course of developing his own "statistical mechanics," based on atoms and mechanics. Continuing in this work, Einstein used mechanics, atoms, and statistical arguments to achieve what he called a "general molecular theory of heat," confirming that both laws of thermodynamics are, indeed, fully explicable on mechanical grounds.[2]

Brownian Motion

In his doctoral dissertation, submitted to the University of Zurich in 1905, Einstein developed a statistical molecular theory of liquids. Then, in a separate paper, he applied the molecular theory of heat to liquids in obtaining an explanation of what had been, unknown to Einstein, a decades-old puzzle. Observing microscopic bits of plant pollen suspended in still water, English botanist Robert Brown had noticed in 1828 that the pollen seeds exhibited an incessant, irregular "swarming" motion, since called "Brownian motion." Although atoms and molecules were still open to objection in 1905, Einstein predicted that the random motions of molecules in a liquid impacting on larger suspended particles—such as pollen seeds—would result in irregular, random motions of the particles, which could be directly observed under a microscope. The predicted motion corresponded precisely with the puzzling Brownian motion! From this motion Einstein accurately determined the dimensions of the hypothetical molecules.[3]

By 1908 the molecules could no longer be considered hypothetical. The evidence gleaned from Brownian motion on the basis of Einstein's work was so compelling that Mach, Ostwald, and their followers were thrown into retreat, and material atoms soon became a permanent fixture of our knowledge of the physical world. Today, with the advent of scanning tunneling microscopes, scientists are nearly able to see and even to manipulate actual, individual atoms for the first time—a circumstance that would satisfy even the most entrenched Machian skeptic.

In the course of his fundamental work on applications of statistical methods to the random motions of Newtonian atoms, Einstein discovered a connection between his statistical theory of heat and the behavior of electromagnetic radiation—the first step toward his hoped-for unification of these two fields. Einstein obtained a mathematical expression for the fluctuations, or oscillations, in the average energy of any system, using his statistical theory of heat. He applied this expression to the average energy of thermal radiation—the electromagnetic waves given off by glowing bodies—in a perfectly reflecting box (often called "blackbody radiation"). He obtained results in close agreement with experimental observations. This connection, he declared in obvious understatement, "ought not to be ascribed to chance."[4] For a physicist like Einstein interested in uniting perspectives, the connection provided an extraordinary opportunity. Einstein's fundamental papers on relativity and quantum theory, also submitted in 1905, may be seen as far-reaching explorations of the connection.

Notes

1. John T. Merz, *A History of European Thought in the Nineteenth Century,* 4 vols. (1904-1912), vol. 3, 391; Christa Jungnickel and Russell McCormmach, *The Intellectual Mastery of Nature: Theoretical Physics from Ohm to Einstein,* 2 vols. (1986), vol. 2, 217-20. BACK

2. Albert Einstein, *The Collected Papers of Albert Einstein*, ed. John Stachel et al. (1987-), vol. 2, 41-55; Martin J. Klein, "Fluctuations and Statistical Physics in Einstein's Early Work," in Gerald Holton and Yehudi Elkana, eds., *Albert Einstein: Historical and Cultural Perspectives* (1982); Thomas S. Kuhn, *Black-Body Theory and the Quantum Discontinuity, 1984-1912* (1978). .BACK

3.Albert Einstein, *Investigations on the Theory of Brownian Movement*, ed. R. Fürth, translated by A.D. Cowper (1926, reprinted 1956); Einstein, *Collected Papers,* vol. 2, 170-82, 206-22. BACK

4. Einstein, *Collected Papers,* vol. 2, 107. BACK

David Cassidy *is Professor of Natural Sciences at Hofstra University. He has served as an editor of the Einstein Papers and is author of a number of works in history of physics, including* Uncertainty: The Life and Science of Werner Heisenberg *(1991) and a related Web exhibit,* Heisenberg/Uncertainty.

An Albert Einstein Chronology

1879 (March 14) Born in Ulm, Germany, to Hermann Einstein (1847-1902) and Pauline Koch (1858-1920).
1880 Einsteins move to Munich.
1881 Sister Maja (Maria) born (d. 1951).
1888 Enters Luitpold school in Munich.
1894 Family moves to Italy, Albert stays at Luitpold.
1895 Rejoins family in Pavia, then goes to cantonal school in Aarau, Switzerland.
1896 Renounces German citizenship.
Gets diploma from Aarau, enrolls at ETH (Federal Institute of Technology) in Zurich.
1900 Gets diploma from ETH.
1901 Becomes Swiss citizen.
1902 Employed at patent office, Bern.
1903 Marries Mileva Maric (1875-1948). They have two sons, Hans Albert (1904-1973), who became a successful hydraulic engineer, and Eduard (1910-1965), who fell prey to incurable schizophrenia. A daughter, Lieserl (1902-?) was born before the marriage and apparently put up for adoption--her fate is unknown.
1905 Publishes in the *Annalen der Physik*:
-*Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristishen Gesichtspunkt*, on the quantum of light and the photo-electric effect.
-*Die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen*, on Brownian motion of particles and atomic theory.
-*Elektrodynamic bewegter Körper*, the special theory of relativity.
-*Ist die Trägheit eines Körpers von seinem Energieeinhalt abhängig?*, equivalence of mass and energy.
1907 -*Planckshe Theorie der Strahlung und die Theorie der spezifische Wärme*, quantum theory for solids (specific heats).
-*Relativitätsprinzip und die aus demselben gezogenen Folgerungen*, the principle of general relativity--gravitation is equivalent to acceleration.
1909 Becomes associate professor at University of Zurich.
Further work on quantum theory.
1911 Becomes full professor at Karl-Ferdinand University in Prague.
Predicts bending of starlight at eclipses (but gets the magnitude wrong).
1912 Becomes professor at the ETH in Zurich.
1914 Becomes professor at University of Berlin.
Separates from Mileva and sons.
Outbreak of First World War.
1915 Cosigns "Manifesto to Europeans" separating himself from German militarism.
-*Feldgleichungen der Gravitation*, the general relativity equations.
1916 -*Die Grundlage der allgemeinen Relativitätstheorie*, book laying out the general theory of relativity.
Becomes president of the German Physical Society.
-*Quantentheorie der Strahlung*, derives momentum carried by light quanta; a 1917 paper with the same title explains stimulated emission.
1917 Becomes director of Kaiser-Wilhelm Institute (which supports research in Germany).
-*Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie*, cosmology equations with the "cosmological term" and expanding universe.
1918 End of First World War; revolution in Germany.

1919 Divorced from Mileva. Marries his cousin Elsa Einstein Löwenthal (1876-1936). Her adult daughters by a previous marriage, Ilse (1897-1934) and Margot (1899-1986), had already legally taken the name Einstein.
Bending of light near sun observed at eclipse.
1920 Public attacks on relativity theory and Einstein by anti-Semites.
1921 First visit to United States.
1922 Works on unified field theory.
Visits Far East.
Awarded Nobel Prize in physics "for his services to theoretical physics and in particular for his discovery of the law of the photo-electric effect."
1924 Inauguration of Einstein Institute with "Einstein Tower" in Potsdam.
-*Quantentheorie des einigatomigen idealen Gases*, the "Bose-Einstein" quantum theory of statistical fluctuations.
1927 Begins dialogue on quantum theory interpretation with Niels Bohr at the fifth Solvay Congress.
1929-*Einheitliche Feldtheorie*, widely publicized attempt to unify gravitational and electromagnetic field theories.
1930 Extended visit to United States, chiefly at the California Institute of Technology.
1932 Appointed professor at Institute for Advanced Study, Princeton, intending to divide time between there and Berlin.
1933 Nazis come to power in Germany; Einstein settles in United States.
1935 -*Can quantum-mechanical description of physical reality be considered complete?* (with B. Podolsky and N. Rosen), continuing the debate over interpretation.
1936 Death of Elsa.
1939 Outbreak of Second World War; Einstein signs letter to President Roosevelt warning of possibility of atomic bombs.
1940 Becomes citizen of United States (retaining Swiss citizenship).
1945 Atomic bombing of Hiroshima and Nagasaki; end of Second World War.
1946 Serves as chairman of Emergency Committee of Atomic Scientists.
1948 -*Generalized theory of gravitation*, an example of continuing attempts to find a more universal mathematical approach to field theory.
1952 Offered presidency of Israel, and declines.
1955 (April 18) Dies in Princeton.

Einstein Chronology for 1905

January 6: Second anniversary of marriage to Mileva Maric.

Early March: Begins to submit one-paragraph reviews of recent scientific papers on heat theory to the *Beiblätter zu den Annalen der Physik* — mainly summaries, with occasional critical remarks. By the end of the year 21 of these reviews were published.

March 14: His 26th birthday.

March 17: Sends *Annalen der Physik* his **photoelectricity** paper, "On a Heuristic Point of View concerning the Production and Transformation of Light." Received March 18, published June 9.

May 14: First birthday of son, Hans Albert.

April 30: Submits his University of Zurich doctoral dissertation, "A New Determination of Molecular Dimensions." (Published in 1906.)

May: Sends *Annalen der Physik* his **Brownian Motion** paper, "On the Movement of Small Particles Suspended in Stationary Liquids Required by the Molecular-Kinetic Theory of Heat." Received May 11, published July 18.

Mid-May: Conceives special relativity theory (he later recalled that he sent the paper in for publication five or six weeks after the idea came to him).

June: Sends *Annalen der Physik* his **special relativity theory** paper, "On the Electrodynamics of Moving Bodies." Received June 30, published 26 September.

July 27: Doctorate is approved unanimously by University of Zurich Philosophy II faculty (the degree was formally awarded January 15, 1906).

August: Sends *Annalen der Physik* his doctoral dissertation on **size of molecules**, received August 19, published with slight revisions February 8, 1906. This would become one of Einstein's most frequently cited papers. It shows how to use fluid phenomena to determine Avogadro's Number, which is related to the size of atoms (and for skeptics, their reality).

Late summer: Travels to Serbia with Mileva and their son, visiting friends and Mileva's family.

September: Sends *Annalen der Physik* his **mass-energy equivalence** paper, "Does the Inertia of a Body Depend upon Its Energy Content?" Received September 27, published November 21. This paper contains the concept which would later be written $E=mc^2$.

October-November: Earns a little money by tutoring a student on electricity.

December: Sends *Annalen der Physik* another paper "On the Theory of Brownian Motion," received December 19, published February 8, 1906. This paper improves and extends his mathematical development of the theory.

This chronology draws chiefly on *The Collected Papers of Albert Einstein,* vol. 2, *The Swiss Years: Writings, 1900-1909,* ed. John Stachel, and vol. 5, *The Swiss Years: Correspondence, 1902-1914,* ed. Martin J. Klein, A.J. Kox, and Robert Schulmann (Princeton, NJ: Princeton University Press, 1989, 1993).

Off the Net: Books on Einstein

Compiled by David Cassidy **For selected Web links look here**

Books for Elementary and Middle-School Students

Calaprice, Alice, ed. *Dear Professor Einstein: Albert Einstein's Letters to and from Children*. Amherst, N.Y.: Prometheus Books, 2002.

Goldenstern, Joyce. *Albert Einstein: Physicist and Genius*. Springfield, NJ: Enslow Publishers, 1995.

Heinrichs, Ann. *Albert Einstein*. Milwaukee: World Almanac Library, 2002.

Ireland, Karin. *Albert Einstein*. Englewood Cliffs, N.J.: Silver Burdett Press, 1989.

Macdonald, Fiona. *Albert Einstein*: *Genius behind the Theory of Relativity*. Woodbridge, Conn.: Blackbirch Press, 2000.

Parker, Steve. *Albert Einstein and Relativity*. New York: Chelsea House Publishers, 1995.

Stannard, Russell. *Black Holes and Uncle Albert*. London: Faber and Faber, 1991.

Stannard, Russell. *The Time and Space of Uncle Albert*. London: Faber and Faber, 1989.

Stannard, Russell. *Uncle Albert and the Quantum Quest*. London: Faber and Faber, 1995.

Wishinsky, Frieda. *What's the Matter with Albert? A Story of Albert Einstein*. Toronto: Maple Tree Press, 2002

Books for a General Audience

Mainly Biographical

Brian, Denis. *Einstein: A Life*. New York: John Wiley, 1996.

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Fölsing, Albrecht. *Albert Einstein: A Biography*. Ewald Osers, transl. New York: Viking, 1997. *The most complete and up-to-date biography (except for the science).

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Friedman, Alan J. and Carol C. Donley. *Einstein as Myth and Muse*. Cambridge: Cambridge University Press, 1985.

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Sayen, Jamie. *Einstein in America: The Scientist's Conscience in the Age of Hitler and Hiroshima*. New York: Crown, 1985. *An insightful account.

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Baierlein, Ralph. *Newton to Einstein: The Trail of Light, An Excursion to the Wave-Particle Duality and the Special Theory of Relativity*. New York: Cambridge University Press, 2001.

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Calder, Nigel. *Einstein's Universe: A Guide to the Theory of Relativity* . New York: Viking Press, 1979.

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Gamow, George. *Mr. Tompkins in Paperback*. New York: Cambridge University Press, 1993.

Schwartz, Joseph. *Einstein for Beginners*. Illus. by Michael McGuinness. New York : Pantheon Books, 2003.

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Photographs

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See also "Books for Deeper Study."

Books for Deeper Study

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More Einstein Info & Links

On this site:

- Einstein basic CHRONOLOGY and 1905 CHRONOLOGY
- BOOKS by & about Einstein
- Historical ESSAYS
- SITE CONTENTS & index

Other Websites:

- The biggest set of links: Albert Einstein Online by S. Morgan Friedman; not up-to-date.
- Julia Cochrane's Einstein links include many on the science of relativity.
- NOVA public TV's Einstein and his science with good explanations.
- The American Museum of Natural History's Einstein exhibit has still more on some topics plus Way to Go, Einstein! for kids.
- The Einstein Archives (Jerusalem) offers Einstein for Kids plus a timeline, resources, some online manuscripts, etc.
- The History of Mathematics Archives gives A short Einstein biography with links to biographies of colleagues and forerunners, and brief descriptions of his theories.
- *Time* magazine's eloquent Person of the Century biography.
- A mini-exhibit on Einstein in Princeton.
- From Cambridge scientists, Relativity and Cosmology.
- Einstein's Legacy in science, from the University of Illinois.
- Caltech's Einstein Papers Project is publishing everything he wrote.
- Our main links page includes some choice sites on 20th century physics, including nuclear history.
- The Alsos Digital Library for Nuclear Issues has many annotated references and links, including these items involving Einstein.

Einstein's words:

NOTE: not all quotes may be genuine; check the source!

- A set from the Quotations Page
- Trubin's Quotes & Jokes for kids
- Kevin Harris's set of Brief Einstein Quotes
- Another set of Selected Einstein Quotes from Mountain Man Graphics
- Einstein's Writings on Science and Religion from St. Cloud University.
- A brief essay, Why Socialism? by Einstein.
- Einstein's article, "What is the Theory of Relativity?" (and watch for more on this site)

Pictures:

Note: no matter what the site owner claims, many Einstein pictures on the Web are copyrighted; photographers make their living this way and you must share any profits from their work. Moreover, any commercial use of Einstein's image requires a license from his estate.

- The AIP's Emilio SegrË Visual Archives has over 100 Einstein photos for sale at cost.
- You can also buy copies of the Einstein Photos at Caltech Archives.
- The University of Frankfurt's substantial set of Albert Einstein Pictures.

Miscellaneous:

Gathered here are the "Exits" found in various pages of the main exhibit.

- **Biography and institutions:**
  a short biography of Niels Bohr (Univ. of Sunderland); a Leo Szilard page by Gene Dannen; a Galileo homepage (Rice University); current pages on the Swiss Federal Institute of Technology, the Institute for Advanced Study and the Federation of American Scientists.
- **Historical topics:**
  short histories of quantum theory, of the special relativity theory, and the general relativity theory from the University of St. Andrews; Einstein's article, "What is the Theory of Relativity?" (manuscript and PDF text); a history of the laser by John Talbot; a history of the Nazi persecution of Jews from the U.S. Holocaust Memorial Museum; "Einstein in Princeton" by the Princeton Historical Society; letters to Roosevelt, the FBI file on Einstein.

Einstein's science today:
– Relativity: A. Dogfrey's "Dummies Guide to Special Relativity;" studies of a gravitational lens and a black hole in the M87 galaxy from the Hubble Space Telescope; a page of cosmology links by J. Troeger; information on current tests of general relativity by Stanford University.
– Atoms & quanta: atoms in a crystal seen with the scanning tunneling microscope; the particle adventure from CERN and a look at high-energy physics from FermiLab; quantum mechanics (Fermilab); an overview of string theory (Cornell University); a page on quantum gravity today (Cambridge University).

Einstein Site Contents

Main Exhibit
Has over 100 pages of text and pictures.

Einstein in Brief
A quick sketch of high points of Einstein's life.

CHRONOLOGY: chronology of Einstein facts including a detailed chronology of 1905.

BIBLIOGRAPHY: books by & about Einstein.

TOPICS:

- **Einstein's physics:** his predecessors and colleagues; the quantum of light, special theory of relativity (and $E=mc^2$), the general theory of relativity (and prediction of warped space), theory of stimulated emission (the laser), the debates with Niels Bohr over the quantum, cosmology (the expanding universe), and unified field theory.
- **Political life:** Einstein's early pacifism, world fame, defense of the Weimar Republic, fight with anti-Semitism, examples of his work for social justice (1930s), his letter to Roosevelt on atomic bombs, and postwar work for peace and freedom.
- **Career and home life:** Einstein's childhood, his brain, Swiss education, patent office job, marriage to Mileva, recreations, move to the U.S., and life in later years.

SPECIAL FEATURES:

- **Einstein's voice:** hear him speaking on energy-mass equivalence, the fate of Europe's Jews, and nuclear weapons and peace.
- **Einstein's science today:** peek at the atomic picture of matter, the quantum, black holes, a gravitational lens, and work towards a unified theory of nature.
- **An essay by Einstein,** "The World as I See It."

ESSAYS by HISTORIANS:

- Einstein's worldview by Gerald Holton
- Einstein's Time by Peter Galison
- How Did Einstein Discover Relativity? by John Stachel
- Einstein on the Photoelectric Effect by David Cassidy
- Einstein on Brownian Motion by David Cassidy

MORE INFORMATION:

- More Einstein info & links

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Making the Exhibit: Who and How

Einstein: Image and Impact is based on a 16-panel travelling exhibit designed by the Center for History of Physics of the American Institute of Physics for the Institute for Advanced Study, Princeton, New Jersey on the occasion of the Einstein Centennial 1879-1979. Expert historians were enlisted to write and check the text, and copies were sent to roughly a thousand sites around the US and abroad in cooperation with the State Humanities Commissions. The exhibit was reformatted for the Web in 1996. Since then additional information about Einstein's life has come to light and has been incorporated in the text, with the advice of leading historians. In 2003-2004 in preparation for the 2005 World Year of Physics and Einstein Great Papers Centennial, the exhibit was reformatted for a better appearance and functionality on current browsers and provided with more supplementary materials.

We have been helped by viewers who pointed out minor errors and places where the text was not entirely clear.
Send us your COMMENTS

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