Brownrigg's *Betel Cutters from the Samuel Eilenberg Collection* (1992), helped create a niche for these objects in the art collectors' world.

Eilenberg led a full and active life till, in 1995, in New York City, he suffered a stroke. He remained mentally alert but was bedridden; sadly, he lost his ability to speak. His health remained frail. In June 1997, he fell into a coma, a state in which he lingered until his death of cardiac arrest at a geriatric center in New York City in January 1998, at the age of eighty-four.

BIBLIOGRAPHY

WORKS BY EILENBERG

With Saunders Mac Lane. "General Theory of Natural Equivalences." *Transactions of the American Mathematical Society* 58 (1945): 231–294. This modest paper is generally considered the birthplace of category theory.

With Norman Steenrod. *Foundations of Algebraic Topology.* Princeton, NJ: Princeton University Press, 1952.

With Henri Cartan. *Homological Algebra.* Princeton, NJ: Princeton University Press, 1956. Translated into Spanish and Russian.

With Calvin C. Elgot. *Recursiveness.* New York: Academic Press, 1970.

Automata, Languages, and Machines. 2 vols. New York, Academic Press, 1974–1976.

With Saunders Mac Lane. *Eilenberg-Mac Lane, Collected Works.* Orlando, FL: Academic Press, 1986.

OTHER SOURCES

Bass, Hyman, et al. "Samuel Eilenberg (1913–1998)." *Notices of the American Mathematical Society* 45, no. 10 (1998): 1344–1352. An extended memorial article.

Brownrigg, Henry. *Betel Cutters: From the Samuel Eilenberg Collection.* London; New York: Thames and Hudson, 1992.

Lerner, Martin, and Steven Kossak. *The Lotus Transcendent: Indian and Southeast Asian Art from the Samuel Eilenberg Collection.* New York: Metropolitan Museum of Art, 1991.

Pace, Eric. "Samuel Eilenberg, 84, Dies; Mathematician at Columbia." *New York Times,* 3 February 1998, p. B9.

Hyman Bass

EINSTEIN, ALBERT

(*b.* Ulm, Germany, 14 March 1879; *d.* Princeton, New Jersey, 18 April 1955) *physics.* For the original article on Einstein see *DSB,* vol. 4.

This essay extends and corrects the original entries by Martin J. Klein and Nandor L. Balazs, drawing on recent work in a variety of areas: experimental tests of general relativity and the role of the cosmological constant; new topics based on recently available information, such as the Einstein family business and its influence on young Einstein; his love affairs, first and second marriages, and other women in his life; black hole physics; and inadequate discussions of the nature of Einstein's light quantum hypothesis; the reasons for his discontent with quantum mechanics; the origins of special relativity and the role of local time; the development of general relativity and the role of metric, affine connection, and Riemann tensor in the theory; his views on the significance of general relativity and the relation between physics and geometry; and his hopes for a unified field theory.

Einstein Family Business. The Einstein brothers' Munich electrical engineering firm built and installed dynamos, power plants, and electric lighting systems, largely invented and patented by Albert's uncle Jakob (1850–1912), an engineer. The new, enlarged factory, started in 1885 with financial help from his mother Pauline's (1858–1920) wealthy father, was managed by his father Hermann (1847–1902), a businessman. The dynamo division alone employed some fifty people. The firm was initially rather successful, and total employment at its height has been estimated at 150–200 (for the family business in Munich, see Hettler, 1996). But after an acrimonious dispute with its larger German rivals, the firm lost the lighting contract for the city of Munich in 1893.

The brothers decided to move to Northern Italy, where they had already installed several power plants, and in 1895 they built a large factory in Pavia. Their efforts to secure a contract to supply the city with electrical power failed due to various local intrigues, and they again had to liquidate their firm in 1896, losing almost everything in the process (for the Italian firm, see Winteler-Einstein, 1924). Uncle Jakob went to work for another firm but, despite Albert's warnings, his father opened a small electrical firm in Milan. Albert helped out from time to time during school vacations, but was able to finish his education only with financial help from his mother's wealthy family.

Prematurely aged by his financial troubles, Hermann died in 1902 deeply in debt to Rudolf Einstein (1843–1928), his cousin and brother-in-law. Young Albert had just started work at the Swiss Patent Office and was unable to support his mother or sister Maja (1881–1951). He had originally been destined to take over the family business and, as an adolescent, demonstrated considerable technical aptitude in electrotechnology, which later stood him in good stead at the Patent Office (1902–1909). But his father's business failures and the attendant stress on the family contributed to an aversion to commercial activities for profit that ultimately led to his critique of capitalism and espousal of socialism (for Albert's early development, see *The Collected Papers*, vol. 1, passim; and John Stachel, "New Introduction" to Einstein, 2005). "I was also originally supposed to be a technical worker. But the thought of having to expend my inventive power on things, which would only make workaday life more complicated with the goal of dreary oppression by capital, was unbearable to me" (translation from Stachel, 2005, "New Introduction," p. xxxiii; see Einstein, 1949, for his later condemnation of the profit system).

Einstein's Love Affairs. The plaster saint image of Einstein, carefully cultivated by his executors, has been shaken by the disclosure of his many love affairs before, during, and after his two marriages. There is now a danger that the myth of the white-haired saint will be replaced by that of a devil incarnate ("father of the atom bomb," "plagiarist," "thief of his wife's ideas"), but what is starting to emerge is something much more interesting than saint or devil: the rounded portrait of a human being (for a discussion of some common myths, see Brian, 2005).

While a student at the Aargau Kantonsschule (a Realschule, not a Gymnasium) in Aarau (1895–1896), Einstein boarded with the family of Jost ("Papa," 1846–1929) Winteler, a teacher at the school and his wife Pauline ("Momma," 1845–1906), with whom he developed close and lasting relationships. His sister later married Paul (1882–1952), one of the Winteler sons, and he had a brief love affair with their daughter Marie (1877–1957), which she later described as "innig [deep]" but "durchaus ideal [completely ideal]." It ended when he moved to Zurich in 1896 to attend the Zurich Poly (1896–1900), where he met Mileva Marić (1875–1948), the only other physics student to enter the program for teachers of mathematics and physics. The two began to study physics together and became intensely involved emotionally during their last years at the Poly. His letters to her from this period (see Einstein, 1992) are the major contemporary source of information on his scientific interests before his first published paper (1901). There is no evidence in his letters or in hers to support claims that she played more than a supporting role in his early research activities (for discussions of their relationship, see Stachel, 2002c; Stachel, 1996; and Martinez, 2005); she was the first of a series of "sounding boards" that he needed in order to help put the fruits of his research, carried out alone and with the aid of non-verbal symbolic systems, into a form that could be communicated to others (for further discussion, including an account of his mode of thought, see the "Introduction to the Centenary Edition" of Einstein, 2005).

After he graduated (she failed the final examinations twice due to poor grades in mathematics), they had a daughter out of wedlock, Lieserl (b. 1902), whose fate is unknown. But they lived apart until his job at the Swiss Patent Office (1902–1909) enabled their marriage in 1903. During these years Einstein did much of his research during working hours, and later stated, "The work on the final formulation of technical patents was a true blessing … and also provided important inspiration for physical ideas" (Einstein, 1956, p. 12). His first biographer reports: "He recognizes a definite connection between the knowledge acquired at the patent office and the theoretical results which, at that same time, emerged as examples of the acuteness of his thinking" (Moszkowski, 1921, p. 22).

In 1909 Einstein obtained his first academic post in theoretical physics at the University of Zurich, and his career slowly began to prosper, with successive posts in Prague and the Zurich Poly. He drifted away from Marić, later attributing his alienation to her taciturnity, jealousy, and depressive personality. By 1912 he was having an affair with Elsa Löwenthal (1876–1936), his cousin and childhood friend. She was a divorcee living in Berlin with her parents—her father Rudolf had been his father's chief creditor. Albert's move to Berlin in 1914 as a newly-elected member of Prussian Academy of Sciences precipitated a crisis in the marriage and Mileva returned to Zurich with their two sons, where she remained for the rest of her life.

After Albert's divorce from Mileva and marriage to Elsa in 1919, he continued to have numerous affairs. In Berlin, the women included Betty Neumann, his secretary; Tony Mendel; and Margarete Lebach; after his move to Princeton in 1933 they included Margarita Konenkova, a Russian citizen living in the United States who has been accused of being a spy (see Pogrebin, 1998, for excerpts from his letters to Konenkova after her return to Russia in 1945; and Schneir, 1998, for contradictions in the spy story). His last close companion was Princeton librarian Johanna Fantova, an old friend from Europe (see Calaprice, 2005 for Fantova's diary of her conversations with Einstein).

Einstein's Light Quantum Hypothesis. In 1905 Einstein characterized only one of his papers as "very revolutionary," the one that "deals with radiation and the energetic properties of light." Klein comments: "Einstein leaped to the conclusion that the radiation … must consist of independent particle of energy" (p. 315), but a reading of the 1905 light quantum paper shows that he did not. He characterizes his demonstration that, in a certain limit, black body radiation behaves as if it were composed of energy quanta, as "a heuristic viewpoint"; and in 1909 warned against just this misunderstanding: "In fact, I am not at all of the opinion that light can be thought of as composed of quanta that are independent of each other and localized in relatively small spaces. This would indeed be the most convenient explanation of the Wien region of the radiation spectrum. But just the division of a light ray at the surface of a refracting medium completely forbids this outlook. A light ray divides itself, but a light quantum cannot divide without a change of frequency" (Einstein to H. A. Lorentz, 23 May 1909, Collected Papers, vol. 5, p. 193). It was only in 1915 that other considerations led him to attribute momentum to a light quantum (see p. 317), and only a decade later, after Bose's work (see pp. 317–318) had shown that elementary particles need not be statistically independent, did he describe them as particles (see Stachel, 2000).

Speaking of Einstein's first paper on mass-energy equivalence, Balazs writes: "[Einstein] observed that the exchange of radiation between bodies should involve an exchange of mass; light quanta have mass exactly as do ordinary molecules" (p. 323). But in his derivation of this result, Einstein speaks about a "light complex," an entirely classical concept, rather than about a light quantum. In his early works, Einstein never mixed concepts from his quantum papers with those from his relativity papers. And when, after Bose's work, he did attribute corpuscular properties to light quanta, he distinguished clearly between photons (a word he did not use), zero rest mass bosons (another word introduced later) whose number need not be conserved; and massive bosons, whose number must be conserved. His prediction of a condensed state for massive bosons (see Einstein, 1925), now called a Bose-Einstein condensate, offered the first theoretical explanation of a transition between two phases of a system. The prediction was spectacularly confirmed some seventy years later, winning its discoverers the 2001 Nobel prize in physics.

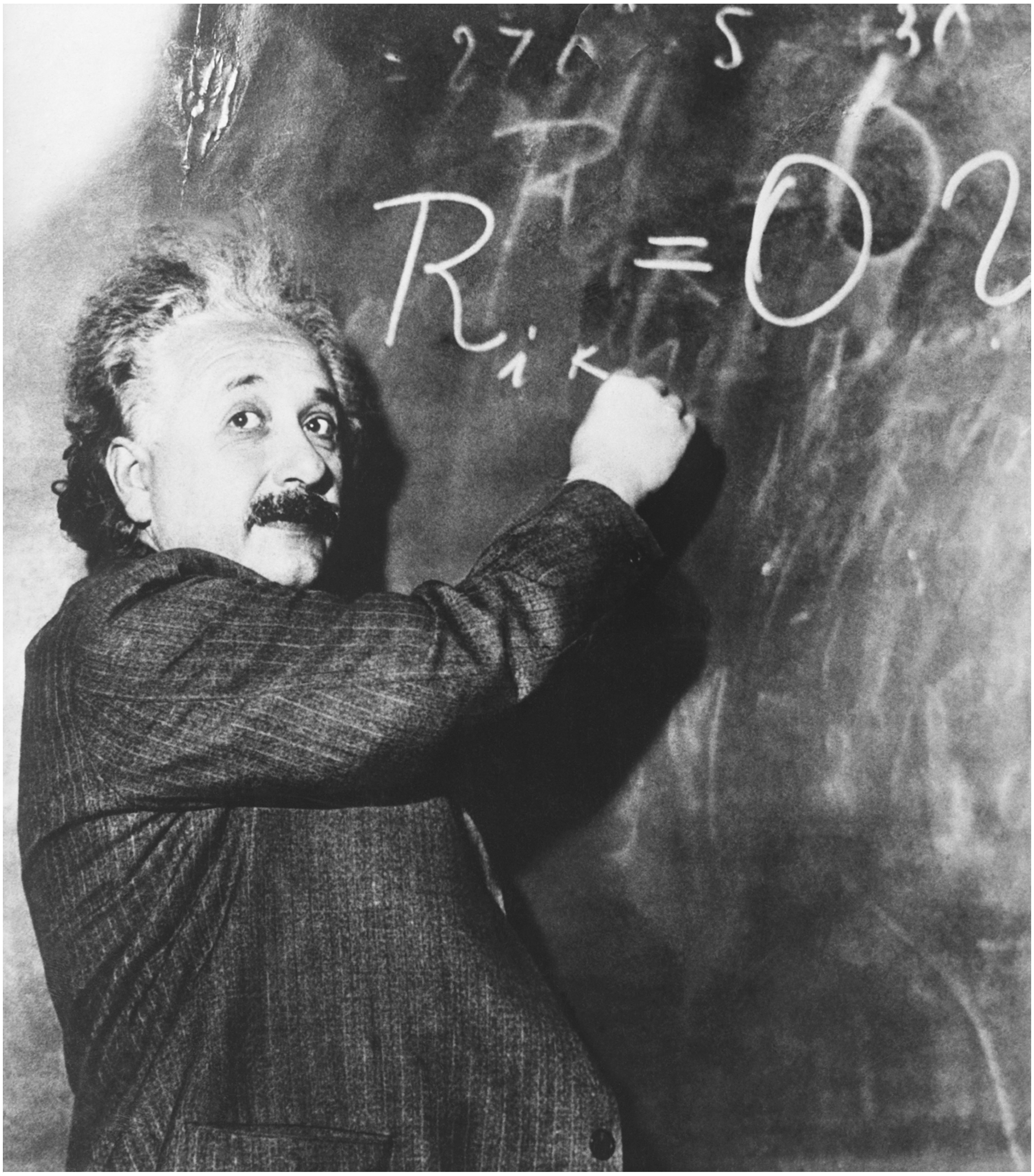
Discontent [*Unbehagen*] with Quantum Mechanics. Speaking of Einstein's "Discontent with Quantum Mechanics," Klein cites (p. 318) its basically statistical nature and presumed incompleteness as the reasons. Actually, Einstein believed that, if one adopted the statistical ensemble interpretation of quantum mechanics (which he referred to as the Born interpretation, but had actually adumbrated; see Stachel, 1986, Sections 5 and 7), there was no problem with the theory. For him, the problem came when the theory was applied to an individual system: it was here that the issue arose of completeness of the quantum mechanical description. A careful reading of his comments on this topic (see Stachel, 1986) shows that the issue of non-separability was the most fundamental cause of his "*Unbehagen.*" As Wolfgang Pauli explained: "Einstein does not consider the concept of 'determinism' to be as fundamental as it is frequently held to be. … he *disputes* that he uses as a criterion for the admissibility of a theory the question 'Is it rigorously deterministic?'" (Pauli to Max Born, 31 March 1954, quoted from Stachel, 1991, p. 411). Once they interact, two quantum systems remain entangled, no matter how far apart in time and space they may have traveled. To Einstein, this seemed to contradict his expectation, based on the role of space-time in his relativity theories, that two systems, sufficiently separated in space-time, should not exert any physical influence on each other.

> Does it make sense to say that two parts *A* and *B* of a system do exist independently of each other if they are (in ordinary language) located in different parts of space at a certain time, if there are no considerable interactions between those parts … at the considered time? … I mean by "independent of each other" that an action on *A* has no immediate influence on the part *B*. In this sense I express a principle a) independent existence of the spatially separated. This has to be considered with the other thesis b) the ψ-function is the complete description of the individual physical situation. My thesis is that a) and b) cannot be true together …. The majority of quantum theorists discard a) tacitly to be able to conserve b). I, however, have strong confidence in a), so I feel compelled to relinquish b). (Einstein to Leon Cooper, 31 October 1949, quoted from Stachel, 1986, p. 375)

Since then the formulation of Bell's inequality and its experimental testing by Clauser, Horne, and Shimony, and by Aspect, have convinced most physicists that quantum entanglement is not the result of an incompleteness due to neglected statistical correlations, as Einstein suggested. Whatever the ultimate fate of contemporary quantum mechanics, entanglement seems destined to remain a fundamental feature of any future physical theory (for a review of this topic, with references to the original literature, see Shimony, 2006).

Origin of Special Relativity. Balazs points out: "By [Einstein's] own testimony the failure of the ether-drift experiments did not play a determinative role in his thinking but merely provided additional evidence in favor of his belief that inasmuch as the phenomena of electrodynamics were 'relativistic,' the theory would have to be reconstructed accordingly" (p. 320). In fact, the phenomena of the optics of moving bodies also played a major role in the development of his ideas. In 1952 he wrote: "My direct path to the special theory of relativity was mainly determined by the conviction that the electromotive force induced in a conductor moving in a magnetic field is nothing other than an electric field. But the result of Fizeau's experiment and the phenomenon of aberration also guided me" (quoted from Stachel, 1989, p. 262).

As Balazs explains (p. 320), the conductor-magnet example suggested to Einstein that the relativity principle must be extended from mechanics to electromagnetic theory. He then attempted to reconcile the relativity principle with well-known optical phenomena, in particular the



Albert Einstein. *Physicist Albert Einstein writing an equation on a blackboard.* © BETTMANN/CORBIS.

constancy of the velocity of light. Two main alternatives presented themselves: (1) The velocity of light is independent of that of its source, constant relative to the ether; or (2) The velocity of light is constant relative to its source (ballistic theory of light—light behaves like a bullet).

Lorentz's version of Maxwell's theory, based on the first alternative, was able to explain the result of Fizeau's experiment and the phenomenon of aberration, but did not seem to be compatible with the relativity principle—the ether frame of reference is special. So Einstein explored the second alternative, where the situation was just the reverse: The relativity principle presented no problem if one assumed that a moving medium dragged the ether along within it. But Fizeau's experiment on the velocity of light in moving water, interpreted within the framework of an ether theory, seemed to preclude the idea that ether was totally dragged along by matter. Rather, it confirmed Fresnel's formula, which had been developed to account for aberration and predicted a partial dragging of the ether (see Stachel, 2005a).

Attempts to explain Fizeau's experiment using the second alternative led to more and more complications, so Einstein returned to the first, but with a crucial difference: he dropped the ether. He realized that the relativity principle then requires the velocity of light to be a universal constant, the same in all inertial frames of reference. But how is this possible? He pondered this question for several years. Finally in 1905 came the insight that removed the puzzle. It is possible if one gives up the Galileian law of addition of relative velocities! A reanalysis of the concept of time showed that the proof of this law depended on the existence of an absolute time, which implies that one can always say whether two events are simultaneous, however far apart. But careful analysis of the concept of simultaneity showed that one must *define* when two events occurring at some distance from each other are simultaneous. He showed that one could adopt definition that made the velocity of light the same in all inertial frames—but this definition gives a different answer in each inertial frame and results in a new law for addition of relative velocities.

Einstein's new definition of frame-dependent time is closely related to Lorentz's concept of local time, as Balazs points out "Although Lorentz appears to have viewed local time as a mathematical artifice, it represented in embryo a concept of time that Einstein would later justify adopting for the whole of physics" (p. 321). In 1900 Poincaré had given a physical interpretation of the local time within the ether-theoretical framework: It is the time that clocks in a moving frame of reference would read (compared with clocks at rest in the ether, which read the true, absolute time) if they were synchronized using light signals, but without correcting for the effects of motion through the ether on the propagation of light. Einstein may well have been familiar with Poincaré's work, but his crucial idea was to drop all reference to the ether and accept the local time of each inertial frame as just as good as that of any other.

Development of General Relativity. Einstein divided his work on general relativity into three key steps (for the first two steps, see Stachel, 2002b; for the third step, see Janssen et al., 2007, vol. 2.).

The first step, in 1907, was his "basic idea for the general theory of relativity" (Stachel, 2002b, p. 261). He was referring to his formulation of the equivalence principle—the inability to uniquely separate gravitation and inertia. Balazs states: "Einstein published two remarkable memoirs in 1912 which were efforts to construct a complete theory of gravitation incorporating the equivalence principle" (p. 326). Actually, they were an attempt to construct equations only for a static field, as well as the equations of motion of a test particle in such a field. His recognition that the latter equations describe the geodesics of a non-flat space-time was a major clue that led to the second step, in 1912: his "recognition of the non-Euclidean nature of the metric and of its physical determination by gravitation" (Stachel, 2002b, p. 261). He was referring to the adoption of the metric tensor as the representation of the gravitational potentials.

The third step came with his "1915 field equations of gravitation. Explanation of the perihelion motion of Mercury" (Stachel 2002b, p. 261). Einstein was referring to the final form of the field equations, which he announced on 25 November 1915. This corrects the erroneous date of 25 March given in the table on p. 324 and on p. 327. The correct date, when combined with Balazs' statement: "[O]n 20 November, David Hilbert, in Göttingen, independently found the same field equations" (p. 327). might suggest that Hilbert actually had priority, a claim that is still maintained by some scholars in the face of new evidence to the contrary (for a review of Hilbert's role in the development of general relativity, see Renn and Stachel, 2007).

Role of the Affine Connection. A fourth key step may be added: Recognition of the affine connection and parallel displacement as the correct mathematical representation of the inerto-gravitational field (for a discussion of the role of the affine connection in the development of gravitation theory, see Stachel, 2007). This step was first taken by Tullio Levi-Civita in 1917, but Einstein came to recognize its crucial importance:

> It is the essential achievement of the general theory of relativity that it freed physics from the necessity of introducing the "inertial system" (or inertial systems). (*The Meaning of Relativity*, p. 139)
>
> The development … of the mathematical theories essential for the setting up of general relativity had the result that at first the Riemannian metric was considered the fundamental concept on which the general theory of relativity and thus the avoidance of the inertial system were based. Later, however, Levi-Civita rightly pointed out that the element of the theory that makes it possible to avoid the inertial system is rather the infinitesimal [parallel]

> displacement field Γ^l_{ik}. The metric or the symmetric tensor field g_{ik} which defines it is only indirectly connected with the avoidance of the inertial system in so far as it determines a displacement field. (*The Meaning of Relativity*, p. 141)

The mathematical formulation of the equivalence principle is that "the displacement field," also called the affine connection, represents a single inertio-gravitational field.

In all previous physical theories, including the special theory, the space-time structures, metric and connection, had been fixed, background fields, determining the kinematics of space-time: the stage, on which the drama of matter and dynamical fields takes place. With the dynamization of these space-time structures, the stage now became part of the play; moreover a new kind of physics was born, now called background-independent to contrast it with all theories based on fixed background space-time.

Balazs writes: "Gravitation is a universal manifestation because it is a property of space-time, and hence everything that is in space-time (which is, literally, everything) must experience it" (p. 331). But Einstein opposed such a "container" or absolute concept of space-time and forcefully advocated a relational approach to space-time (see, for example, Einstein, 1954), preferring to say that space-time is a property of the gravitational field:

> [A]ccording to the special theory of relativity, space (space-time) has an existence independent of matter or field. In order to be able to describe at all that which fills up space …, space-time or the inertial system with its metrical properties must be thought of at once as existing, for otherwise the description of "that which fills up space" would have no meaning. On the basis of the general theory of relativity, on the other hand, space as opposed to "what fills space" … has no separate existence. … If we imagine the gravitational field, i.e., the functions g_{ik} to be removed, there does not remain a space of the type (1) [Minkowski space-time], but absolutely *nothing*, and also no "topological space". … There is no such thing as an empty space, i.e., a space without field. Space-time does not claim existence on its own, but only as a structural quality of the field. (Einstein, 1952, p. 155).

Balazs writes: "In this way Einstein showed that gravitational fields influence the motion of clocks" (p. 325). Presumably, Balazs meant the rate of clocks, but even that statement would be inaccurate. General relativity is built precisely on the assumption that (ideal) clocks and measuring rods are *not* affected by the presence of an inertio-gravitational field. However, the rates of two clocks at different places in a gravitational field cannot be directly compared. (If the two clocks are brought to the same place for direct comparison, according to general relativity they will always agree!) Some signal must pass between them. It is the difference between the frequency with which a signal is emitted by one clock and the frequency with which the signal is detected at the position of the other clock that is responsible for gravitational effects on time measurements, such as the gravitational red shift.

Balazs writes "In particular [Einstein] assumed that … the history of a body will be a geodesic … the curve in space-time for which $\int ds$ is a minimum, $\delta \int ds = 0$" (p. 227). While this integral is always an *extremal* of the space-time interval for geodesic curves, for time-like paths it is a *maximum.* This is the basis of the twin paradox: The stay-at-home, non-accelerating twin will be much older than his adventurous, accelerating sibling when the two meet again.

Balazs writes "$\Theta_{\mu\nu}$ contains the material sources of the field … In any given physical situation, the $\Theta_{\mu\nu}$ may be assumed known" (p. 227). In fact, the expression for $\Theta_{\mu\nu}$, the stress-energy-momentum tensor (later in the article symbolized by $T_{\mu\nu}$), almost always contains the metric tensor, so the gravitational field equations cannot be solved separately. Rather, one must solve the coupled sets of equations for the source fields and for the metric field.

Curvature Tensors and Field Equations. Balazs writes "[T]he gravitational field can be characterized by Riemann's curvature tensor $G_{\mu\nu}$ …. [Einstein] wrote the gravitational field equations as $G_{\mu\nu} = K(T_{\mu\nu} - 1/2\, g_{\mu\nu} T)$, where T is the scalar of the material energy tensor $T_{\mu\nu}$ and K is a gravitational constant. … The curvature of space-time at a point is determined by the amount of matter and electromagnetic field and their motion at that point" (p. 328). There are several errors here. First, Balazs' $G_{\mu\nu}$ is the Ricci tensor, not the Riemann curvature tensor. The Riemann tensor is a four-index tensor $R^{\kappa}{}_{\mu\lambda\nu}$, the trace of which is equal to the Ricci tensor: $R^{\kappa}{}_{\mu\kappa\nu} = G_{\mu\nu}$, in Balazs' notation. The Ricci tensor is more commonly denoted by $R_{\mu\nu}$, whereas $G_{\mu\nu}$ is used to denote the Einstein tensor $R_{\mu\nu}-1/2\, g_{\mu\nu} R$, where R is the trace of the Ricci tensor. The gravitational field equations are now more commonly written in the form: $R_{\mu\nu} - 1/2\, g_{\mu\nu} R = KT_{\mu\nu}$, which is equivalent to Einstein's original form.

Second, according to Einstein, it is the affine connection that defines the inertio-gravitational field, not the Riemann tensor:

> What characterizes the existence of a gravitational field from the empirical standpoint is the non-vanishing of the Γ^l_{ik} [components of the affine connection], not the non-vanishing of the R_{iklm} [the components of the Riemann tensor]. If one does not think in such intuitive ways, one cannot

> comprehend why something like curvature should have anything at all to do with gravitation. (Einstein to Max von Laue 1950; English translation from Stachel, 1989, p. 326)

The affine connection is not a tensor between systems of such particles. The Riemann tensor is built from its components and their first derivatives. The affine connection enters the geodesic equation—it would actually be better to say the equation for autoparallel or straightest lines—describing the motion of freely falling sructureless particles, while the Riemann tensor enters the equation of geodesic deviation, which characterizes the tidal gravitational forces between such particles.

A metric affine connection, as in general relativity, is built from the components of the metric and their first derivatives. In this case, the autoparallel lines are also metric geodesics. It follows that a metric Riemann tensor depends on the metric tensor and its first and second derivatives. In spite of Einstein's comments cited above, general relativity is still often presented entirely in terms of the metric tensor and its derivatives, without proper emphasis on the role of the connection.

The third error is that the curvature at a point of space-time is *not* "determined by the amount of matter and electromagnetic field and their motion *at that point*." The Riemann tensor determined by a metric has twenty independent components at each point, and only the ten components of the Ricci tensor are so determined. It is the additional ten components that enable the propagation of gravitational waves, even in "empty" regions of space-time, that is, regions in which the Ricci tensor vanishes.

Tests of the General Theory. The theory has survived much more precise observations of the three classic predictions: the anomalous precession of Mercury's orbit, the gravitational red shift, and the apparent bending of light beams in strong gravitational fields. Indeed, the relativistic effects are now so well confirmed that they are routinely used in many new applications (for surveys, see Damour, 2006 and Will, 2005).

The gravitational bending effect is the basis of the phenomenon known as gravitational lensing, originally predicted by Einstein around 1912, but not published by him until 1936 (for Einstein's role, see Renn, Sauer, and Stachel, 1997). It is now a major tool in observational cosmology, particularly the study of the effects of "dark matter" in galaxies and clusters on light propagation (for gravitational lensing, see Schneider, Ehlers, and Falco, 1992). On a more everyday level, the ubiquitous Global Positioning System (GPS) could not operate without taking into account both special and general relativistic effects (see Ashby, 2005).

The major outstanding project is the direct detection of gravitational waves. Indirect confirmation of the emission of quadrupole gravitational radiation by the binary pulsar PSR 1913+16 through measurement of the resulting modification of the presumed back reaction on their orbits has been extremely successful, winning its observers the Nobel Prize for Physics in 1993 (see Will, 2005). But instruments designed to detect the radiation itself, notably the Laser Interferometer Gravitational-Wave Observatory (LIGO), did not attain sufficient sensitivity to "see" the extremely weak radiation predicted from astrophysical sources (see Saulson, 2005), or the even weaker background cosmological gravitational radiation predicted by some models of the early universe.

The Cosmological Constant. As Balazs points out, Einstein originally introduced the cosmological constant Λ in 1916 order to implement what he called Mach's principle: On a cosmological scale, the metric tensor field should be completely determined by matter. Einstein took it for granted that, on the average, the universe was static, so he developed such a static cosmological model, for which he needed Λ. When Alexander Friedmann first showed that there are non-static cosmological models with and without the cosmological constant, Einstein thought he had found an error in Friedmann's work. He quickly withdrew that claim, but regarded the expanding universe solutions as mere mathematical curiosities until the observations of Hubble around 1930 showed their importance for cosmology. By this time Einstein had abandoned Mach's principle in favor of the reverse, unified field viewpoint: The properties of matter should be completely determined by solutions to some set of unified field equations. Thus, the cosmological constant was no longer needed for its original purpose and there were expanding cosmological models without it, so Einstein abandoned the concept. Others, such as Eddington, kept Λ for other reasons, and it maintained a precarious foothold in cosmological speculations.

In the latter third of the twentieth century, the situation in cosmology began to change dramatically. Theoretical cosmology became more and more closely associated with elementary particle theory, and observational cosmology began to accumulate more and more data limiting the possibilities for and influencing the construction of cosmological models. The cosmological constant has had a dramatic rebirth with the accumulating observation evidence that, rather than slowing down as current theories had predicted, the expansion of the universe is actually accelerating with cosmic time. By an appropriate choice of sign and value for Λ, cosmological models with this property are easily constructed. The problem is to give a physical explanation for such a choice of Λ. One favored explanation as of 2007 is that the Λ-term in the field equations is actually the stress-energy-momentum tensor for "dark energy," a hitherto unobserved component pervading the entire universe. If this explanation stands the test of time, it may also turn out that the "cosmological constant" is not constant, but varies with cosmological time! (For a review of developments in cosmology, see Padmanabhan, 2005.)

Black Hole Physics. Since the original edition of the *DSB*, an entire industry has grown up within theoretical physics and observational astronomy known as "black hole physics" (for reviews, see Carter, 2006, and Price, 2005). It is based theoretically on the existence of two solutions to the homogeneous Einstein field equations: the static, spherically symmetric Schwarzschild solution, dating from 1916, and the stationary, axially symmetric Kerr solution, dating from 1963. (For reviews of these and other exact solutions to the Einstein equations, see Bičak, 2000.) Astrophysics predicts that sufficiently massive astrophysical objects ultimately undergo gravitational collapse as gravitation overwhelms the pressures and stresses that keep them from collapsing. If they are massive enough, this process will not be halted by the formation of a neutron star, but will continue until the system passes through an event horizon and forms a black hole, which ultimately ends in a singularity, signaling the breakdown of classical general relativity. This is the upshot of the famous Penrose-Hawking singularity theorems. The external gravitational field outside the horizon must ultimately take the form of either the Schwarzschild field if the system has no net angular momentum, or the Kerr solution if it does. This result was picturesquely stated as "black holes have no hair" by John Wheeler, who coined the term "black hole." Classically, except for their gravitational fields, such black holes have no influence on their exterior, but Stephen Hawking showed that a semi-classical treatment of quantum-mechanical effects predicts the formation of a radiation field outside the black hole that behaves like black-body radiation at a temperature dependent on the mass of the black hole. Much theoretical work is being done in the early 2000s in the attempt to find an exact quantum-gravitational treatment of black holes, and much observational work on the search for black holes in the cosmos.

Relation Between Geometry and Physics. Balazs asserts: "Minkowski recast the special theory of relativity in a form which had a decisive influence in the geometrization of physics. … This very strong geometrical point of view … led to Einstein's belief that all laws of nature should be geometrical propositions concerning space-time" (p. 323). Einstein's supposed "views on the geometrization of physics" are repeated: "He felt that not only the gravitational but also electromagnetic effects should be manifestations of the geometry of space-time" (p. 325). Although many people continue to hold this view of Einstein's accomplishment and attribute it to him, Einstein explicitly rejected it. In 1928 he wrote: "I cannot agree that the assertion relativity reduces physics to geometry has a clear meaning. One can more correctly say that it follows from the theory of relativity that (metric) geometry has lost its independent existence with respect to the laws usually classified as physical. … That this metric tensor is designated as 'geometrical' is simply connected with the fact that the formal structures concerned first appeared in the science called 'geometry.' But this is not at all sufficient to justify applying the name 'geometry' to every science in which this formal structure plays a role, even when for purposes of visualization [*Veranschaulichung*] representations are used, to which geometry has habituated us. …" He explicitly rejected the idea that the search for a unified field theory was an attempt to geometrize the electromagnetic field: "The essential thing in Weyl's and Eddington's theoretical representations of the electromagnetic field does not lie in their having embedded the field in geometry, but that they have shown a possible way to represent gravitation and electromagnetism from a unified point of view" (Einstein, 1928; translated from the German manuscript, *The Einstein Archives Online*, Call Nr. [1-68.00]). Peter Bergmann has suggested that "physicalization of geometry" would be a more appropriate phrase (see Bergmann, 1979; the phrase had been used in Zubirini, 1934).

Balazs asserts: "[T]he geometrization of gravitation led eventually to the general theory of relativity; the additional geometrization of the electromagnetic fields of force led to the invention of the unified field theories." Apart from the use of geometrization language, criticized above, the statement may be misleading. The most successful "geometrization of the electromagnetic fields of force" has been achieved as part of the modern gauge theory of Yang-Mills fields. This has served to unify the electromagnetic and weak nuclear forces, and to a lesser extent, in the theory of quantum chromodynamics, the strong nuclear forces, in the so-called Standard Model. The formulation and quantization of these theories is based on the mathematics of gauge natural fiber bundles, while the standard formulation of general relativity only requires natural bundles. While classical gravitation theory also can be formulated as a gauge natural bundle theory, as of 2007 no successful quantization based on this approach has been accomplished—let alone a unified quantum theory including gravitation (for natural and/or gauge natural theories see Fatibene and Francaviglia, 2003).

Einstein and Unified Field Theory. Balazs states: "Between 1907 and 1911 … [Einstein] came to understand that the solution to the dualism [of fields and particles] problem was to write physics in terms of continuous field quantities and nonlinear partial differential equations that would yield singularity-free particle solutions" (pp. 325–326). Similarly, Klein states "[Einstein] never lost his hope that a field theory of the right kind might eventually reach this goal" (pp. 318–319). Actually, as early as 1916, Einstein was presenting arguments suggesting that the continuum was too rich a structure for the treatment of quantum phenomena (for the evolution of his ideas between 1902 and 1954, see Stachel, 1993). While he continued to work on the topic, his hopes for a satisfactory unified field theory grew weaker in his later years, as Balazs himself suggests: "In 1953 Einstein said to the author that … it is doubtful that a unified field theory of the type he was seeking could exist" (p. 330).

Here is Einstein's last published comment on the subject, written shortly before he died:

> One can give good reasons why reality cannot at all be represented by a continuous field. From the quantum phenomena it appears to follow with certainty that a finite system of finite energy can be completely described by a finite set of numbers (quantum numbers). This does not seem to be in accordance with a continuum theory, and must lead to an attempt to find a purely algebraic theory for the description of reality. But nobody knows how to obtain the basis of such a theory. ("Appendix II" to *The Meaning of Relativity*, 5th ed. Princeton, 1955, p. 166)

Much recent work on quantum gravity has been based on attempts to set up just such a "purely algebraic theory." For reviews of some attempts, see Gambini and Pullin, 2005; Dowker, 2005; and Ambjorn, Jurkiewicz, and Loll, 2006.

SUPPLEMENTARY BIBLIOGRAPHY

For the Einstein Archives in the Hebrew University of Jerusalem, consult http://www.albert-einstein.org. For the Einstein Papers Project, consult http://www.einstein.caltech.edu. For updated reviews of most topics in general relativity, consult http://relativity.livingreviews.org.

WORKS BY EINSTEIN

"Quantentheorie des einatomigen idealen Gases. Zweite Abhandlung." *Preussische Akademie der Wissenschaften* (Berlin) *Physikalisch-mathematische Klasse. Sitzunsberichte* (1925): 3–14.

"A propos de la déduction relativiste de M. Emile Meyerson." *Revue Philosophique* 105 (1928): 161–166.

"Lens-Like Action of a Star by the Deviation of Light in a Gravitational Field." *Science* 84 (1936): 506–507.

"Why Socialism." *Monthly Review* (May 1949). Reprinted in *Ideas and Opinions*. New York: Crown Publishers, 1954, 151–158.

"Relativity and the Problem of Space." In *Relativity: The Special and the General Theory.* 15th ed. New York: Crown, 1952. Reprinted in *Ideas and Opinions*. New York: Crown Publishers, 1954.

"Foreword." In *Concepts of Space*, by Max Jammer. Cambridge, MA: Harvard University Press, 1954.

"Autobiographische Skizze." In *Helle Zeit- Dunkle Zeit In Memoriam Albert Einstein,* edited by Carl Seelig. Zürich: Europa, 1956.

The Collected Papers of Albert Einstein. Translated by Anna Beck. Princeton, NJ: Princeton University Press, 1987–2004. Vol. 1: *The Early Years, 1879–1902.* Vol. 2: *The Swiss Years: Writings, 1900–1909.* Vol. 3: *The Swiss Years: Writings, 1909–1911.* Vol. 4: *The Swiss Years: Writings, 1912–1914.* Vol. 5: *The Swiss Years: Correspondence, 1902–1914.* Vol. 6: *The Berlin Years: Writings, 1914–1917.* Vol. 7: *The Berlin Years: Writings, 1918–1921.* Vol. 8: *The Berlin Years: Correspondence, 1914–1918.* Vol. 9: *The Berlin Years: Correspondence, January 1919–April 1920.* Vol. 10: *The Berlin Years: Correspondence, May-December 1920, and Supplementary Correspondence, 1909–1920.* Cited as *Collected Papers*. These volumes are making available a wealth of new material about his personal life, his scientific work, and his political-social activities. Each volume has an English translation supplement.

Albert Einstein, Mileva Maric: The Love Letters, edited by Jürgen Renn and Robert Schulmann, translated by Shawn Smith. Princeton, NJ: Princeton University Press, 1992.

Einstein's Miraculous Year: Five Papers that Changed the Face of Physics. New introduction by John Stachel; foreword by Roger Penrose. 2nd ed. Princeton, NJ: Princeton University Press, 2005. Translations of all the 1905 papers, with commentary and notes.

The New Quotable Einstein. Edited by Alice Calaprice; foreword by Freeman Dyson. Princeton, NJ: Princeton University Press, 2005.

The Political Einstein. Edited and translated by David Rowe and Robert Schulmann. Princeton, NJ: Princeton University Press, 2007.

OTHER SOURCES

Ambjorn, Jan, J. Jurkiewicz, and Renate Loll. "Quantum Gravity, or the Art of Building Spacetime." In *Approaches to Quantum Gravity*, edited by Danielle Oriti Cambridge, U.K.: Cambridge University Press, 2007.

Ashby, Niel. "Relativity in the Global Positioning System." In *100 Years of Relativity Space-Time Structure,* edited by Abhay Ashtekar. Hackensack, NJ: World Scientific, 2005.

Ashtekar, Abhay, ed. *100 Years of Relativity Space-Time Structure: Einstein and Beyond.* Hackensack, NJ: World Scientific, 2005.

Bergmann, Peter G. "Unitary Field Theory, Geometrization of Physics or Physicalization of Geometry?" In *Einstein Symposion, Berlin: aus Anlaß der 100. Wiederkehr seines Geburtstages 25. bis 30. März 1979*, edited by Horst Nelkowski, A. Hermann, and H. Poser. Lecture Notes in Physics, vol. 100. Berlin and New York: Springer, 1979.

Bičak, Jiri. "Selected Solutions of Einstein's Field Equations: Their Role in General Relativity and Astrophysics." *Lecture Notes in Physics* 540 (2000): 1–126.

Brian**,** Denis. *The Unexpected Einstein: The Real Man behind the Icon.* Hoboken, NJ: Wiley, 2005.

Carter, Brandon. "Half Century of Black-Hole Theory: From Physicists' Purgatory to Mathematicians' Paradise." In *A Century of Relativity Physics*, edited by Lysiane Mornas and Joaquin Diaz Alonso. Melville, NY: American Institute of Physics, 2006.

Damour, Thibault. "100 Years of Relativity: Was Einstein 100% Right?" In *A Century of Relativity Physics*, edited by Lysiane Mornas and Joaquin Diaz Alonso. Melville, NY: American Institute of Physics, 2006.

Dowker, Fay. "Causal Sets and the Deep Structure of Spacetime." In *100 Years of Relativity Space-Time Structure,* edited by Abhay Ashtekar. Hackensack, NJ: World Scientific, 2005.

Fatibene, Lorenzo, and Mauro Francaviglia, *Natural and Gauge Natural Formalism for Classical Field Theories: A Geometric Perspective including Spinors and Gauge Theories.* Dordrecht, Netherlands, and Boston: Kluwer, 2003.

Fölsing, Albrecht. *Albert Einstein: A Biography.* New York and London: Viking, 1997. Good on biographical information, weak on science.

Gambini, Rodolfo, and Jorge Pullin. "Consistent Discrete Space-Time." In *100 Years of Relativity Space-Time Structure,* edited by Abhay Ashtekar. Hackensack, NJ: World Scientific, 2005.

Goenner, Hubert F. M. "On the History of Unified Field Theories." *Living Reviews in Relativity* 7 (2004). Available from http://relativity.livingreviews.org/lrr-2004-2.

Hettler, Nicolaus. "Die Elektrotechnische Firma J. Einstein u. Cie in München—1876–1894." PhD diss. Stuttgart University, 1996.

Highfield, Roger, and Paul Carter. *The Private Lives of Albert Einstein.* London: Faber, 1993; Boston: St, Martin's, 1994.

Janssen, Michel, John D. Norton, Jürgen Renn, et al. *The Genesis of General Relativity*, vol. 1: *Einstein's Zurich Notebook: Introduction and Source*, vol. 2: *Einstein's Zurich Notebook: Commentary and Essays.* Dordrecht, Netherlands: Springer, 2007.

Martinez, Alberto. "Handling Evidence in History: The Case of Einstein's Wife." *Science School Review 86* (2005): 51–52.

Moszkowski, Alexander. *Einstein, Einblicke in seine Gedankenwelt: Gemeinverständliche Betrachtungen über die Relativitätstheorie und ein neues Weltsystem, Entwickelt aus Gesprächen mit Einstein.* Hamburg, Germany: Hoffmann und Campe, 1921.

Oriti, Daniele, ed. *Approaches to Quantum Gravity.* Cambridge, U.K.: Cambridge University Press, 2007.

Overbye, Dennis. *Einstein in Love: A Scientific Romance.* New York: Viking, 2000.

Padmanabhan, Thanu. "Understanding Our Universe: Current Status and Open Issues." In *100 Years of Relativity Space-Time Structure,* edited by Abhay Ashtekar. Hackensack, NJ: World Scientific, 2005.

Pais, Abraham. *'Subtle is the Lord … ' The Science and the Life of Albert Einstein.* New York: Oxford University Press, 1982. The best overall analysis of Einstein's scientific work.

Pogrebin, Robin. "Love Letters by Einstein at Auction." *New York Times*, 1 June 1998.

Price, Richard H. "The Physical Basis of Black Hole Astrophysics." In *100 Years of Relativity Space-Time Structure,* edited by Abhay Ashtekar.

Renn, Jürgen, and John Stachel. "Hilbert's Foundation of Physics: From a Theory of Everything to a Constituent of General Relativity." In *The Genesis of General Relativity,* vol. 3, *Gravitation in the Twilight of Classical Physics: Between Mechanics, Field Theory and Astronomy*, edited by Jürgen Renn and Matthias Schimmel. Dordrecht, Netherlands: Springer, 2007.

Renn, Jürgen, Tilman Sauer, and John Stachel. "The Origin of Gravitational Lensing: A Postscript to Einstein's 1936 *Science* Paper." *Science 275* (1997): 184–186. Reprinted in Stachel, *Einstein from "B" to "Z."*

Saulson, Peter R. "Receiving Gravitational Radiation." In *100 Years of Relativity Space-Time Structure,* edited by Abhay Ashtekar.

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

Schneider, Peter, Jürgen Ehlers, and Emilio E. Falco. *Gravitational Lenses.* Berlin and London: Springer, 1992.

Schneir, Walter. "Letter to the Editor." *New York Times*, 5 June 1998.

Shimony, Abner. "Bell's Theorem." *Stanford Encyclopedia of Philosophy* (Fall 2006), edited by Edward N. Zalta. Available from http://plato.stanford.edu/archives/fall2006/entries/bell-theorem.

Stachel, John. "Einstein and the Quantum: Fifty Years of Struggle." In *From Quarks to Quasars: Philosophical Problems of Modern Physics*, edited by Robert Colodny. Pittsburgh, PA: University of Pittsburgh Press, 1986. Reprinted in Stachel, *Einstein from "B" to "Z."* Boston, Berlin, and Basel: Birkhauser, 2002a.

———. "Einstein on the Theory of Relativity," 1987. In *Collected Papers*, vol. 1, pp. 253–274. Reprinted in Stachel, *Einstein from "B" to "Z."* Boston, Berlin, and Basel: Birkhauser, 2002a.

———. "Einstein's Search for General Covariance." In *Einstein and the History of General Relativity*, edited by Don Howard and John Stachel. Einstein Studies, vol. 1. Boston/Berlin/Basel: Birkhauser, 1989. Reprinted in Stachel, *Einstein from "B" to "Z."* Boston, Berlin, and Basel: Birkhauser, 2002a.

———. "Einstein and Quantum Mechanics." In *Conceptual Problems of Quantum Gravity,* edited by Abhay Ashtekar and John Stachel. Einstein Studies, vol. 2. Boston, Berlin, Basel: Birkhauser, 1991. Reprinted in Stachel, *Einstein from "B" to "Z."* Boston, Berlin, and Basel: Birkhauser, 2002a.

———. "The Other Einstein: Einstein Contra Field Theory." *Science in Context 6* (1993): 275–290. Reprinted in Stachel, *Einstein from "B" to "Z."* Boston, Berlin, and Basel: Birkhauser, 2002a.

———. “Einstein and Marić: A Collaboration that Failed to Develop.” In *Creative Couples in the Sciences*, edited by Helena M. Pycior, Nancy G. Slack, and Pnina Abir-Am. New Brunswick, NJ: Rutgers University Press, 1996. Reprinted in Satchel, *Einstein from “B” to “Z.”* Boston, Berlin, and Basel: Birkhauser, 2002a.

———. “Einstein’s Light Quantum Hypothesis, or Why Didn’t Einstein Propose a Quantum Gas a Decade-and-a-Half Earlier?” In *Einstein: The Formative Years, 1879–1909*, edited by Don Howard and John Stachel. Boston: Birkhauser, 2000. Reprinted in *Einstein from “B” to “Z.”* Boston, Berlin, and Basel: Birkhauser, 2002a.

———. *Einstein from “B” to “Z.”* Boston, Berlin, and Basel: Birkhauser, 2002a.

———. “The First Two Acts,” 2002b. In *Einstein from “B” to “Z.”* Boston, Berlin, and Basel: Birkhauser, 2002a.

———. “The Young Einstein: Poetry and Truth,” 2002c. In *Einstein from “B” to “Z.”* Boston, Berlin, and Basel: Birkhauser, 2002a.

———. “Fresnel’s (Dragging) Coefficient as a Challenge to 19th Century Optics of Moving Bodies.” In *The Universe of General Relativity*, edited by A. J. Cox and Jean Einsenstaedt. Einstein Studies, vol. 11. Boston, Basel, Berlin: Birkhauser, 2005a.

———. “Introduction to the Centenary Edition,” 2005b. In *Einstein’s Miraculous Year: Five Papers that Changed the Face of Physics.* New introduction by John Stachel; foreword by Roger Penrose. 2nd ed., 2005b. Princeton, NJ: Princeton University Press, 2005.

———. “The Story of Newstein: Or Is Gravity Just Another Pretty Force?” In *The Genesis of General Relativity,* vol. 4, *Gravitation in the Twilight of Classical Physics: The Promise of Mathematics*, edited by Jürgen Renn and Matthias Schimmel. Berlin: Springer, 2007.

Will, Clifford. “Was Einstein Right? Testing Relativity at the Centenary.” In *100 Years of Relativity Space-Time Structure,* edited by Abhay Ashtekar. Hackensack, NJ: World Scientific, 2005.

Winteler-Einstein, Maja. “Albert Einstein—Beitrag für Sein Lebensbild,” 1924. In *Collected Papers*, vol. 1.

Zubirini, Xavier. “La idea de naturaleza: la nueva fisica.” Translation in *Nature, History, God.* Washington, DC: University Press of America, 1981.

John Stachel

ELION, GERTRUDE BELLE (*b.* New York, New York, 23 January 1918; *d.* Chapel Hill, North Carolina, 21 February 1999), *pharmacology, antimetabolites, immunosuppressors, anticancer drugs, antiviral drugs.*

Elion shared the 1988 Nobel Prize in Physiology or Medicine with James Black, who discovered beta-blockers and H_2–receptor antagonists, and George H. Hitchings, with whom she had collaborated for more than forty years, the two being responsible for the discovery of many major therapeutic agents—anticancer, antiviral, antibacterial, immunosuppressive, anti-gout—whose common characteristic was that they were specifically targeted at nucleic acids. Elion may thus be considered a founder of molecular pharmacology. Although she was the fifth woman to receive the Nobel Prize in Physiology or Medicine, she was the first who was neither a physician nor the holder of a doctoral degree.

Elion was born in New York on 23 January 1918. Her father, Robert Elion, had immigrated from Lithuania at the age of twelve and studied dental surgery in New York. Her mother, Bertha Cohen, had arrived in the United States from the Russian-Polish borderlands at age fourteen. Their daughter graduated from Hunter College in 1937. Academia was scarcely welcoming to women in those days, and she was unable to pursue her studies immediately. She taught for a semester at the New York Hospital School of Nursing and volunteered at a chemistry laboratory. Only in 1939 did she embark on postgraduate studies at New York University, where, two years later, the sole female candidate, she was awarded a master of science degree in chemistry.

When her grandfather died of cancer, Elion began to dream of a career in medical research, but she was obliged to start out as a food analyst for the Quaker Maid Company. The American mobilization for World War II, by opening up many positions to women, gave her a chance to enter the pharmaceutical industry. In 1944, after a few months with Johnson & Johnson, she was offered employment with Burroughs Wellcome as an assistant chemist in the laboratory of Hitchings in Tuckahoe, New York. There she began, ten years before the discovery of the double helix, to investigate modifiers of nucleic-acid metabolism.

Contemporary advances in antineoplastic chemotherapy prompted the reorientation of this research toward cancer. The first concrete results began to appear in 1947, with the formulation of the antileukemics 6-mercaptopurine and 6-thioguanine. Elion and her colleagues subsequently developed azathioprine, a powerful immunosuppressive drug. Another line of inquiry led to allopurinol, a treatment for gout and hyperuricemia.

Elion’s work culminated in a great discovery, that of the strong antiherpetic action of acyclovir. From 1967 on, she headed Burroughs Wellcome’s Experimental Therapy Department. Her name appeared on forty-five patents. She received twenty-five honorary doctorates and was elected president of the American Association for Cancer Research. She entered semiretirement in 1983, but was invited to teach at Duke University (Durham, North Carolina) and at the University of North Carolina at Chapel Hill. She also worked for the World Health Organization