Einstein's Mistakes

Science sets itself apart from other paths to truth by recognizing that even its greatest practitioners sometimes err.

Steven Weinberg

Albert Einstein was certainly the greatest physicist of the 20th century, and one of the greatest scientists of all time. It may seem presumptuous to talk of mistakes made by such a towering figure, especially in the centenary of his annus mirabilis. But the mistakes made by leading scientists often provide a better insight into the spirit and presuppositions of their times than do their successes.[1] Also, for those of us who have made our share of scientific errors, it is mildly consoling to note that even Einstein made mistakes. Perhaps most important, by showing that we are aware of mistakes made by even the greatest scientists, we set a good example to those who follow other supposed paths to truth. We recognize that our most important scientific forerunners were not prophets whose writings must be studied as infallible guides—they were simply great men and women who prepared the ground for the better understandings we have now achieved.

The cosmological constant

In thinking of Einstein's mistakes, one immediately recalls what Einstein (in a conversation with George Gamow[2]) called the biggest blunder he had made in his life: the introduction of the cosmological constant. After Einstein had completed the formulation of his theory of space, time, and gravitation—the general theory of relativity—he turned in 1917 to a consideration of the spacetime structure of the whole universe. He then encountered a problem. Einstein was assuming that, when suitably averaged over many stars, the universe is uniform and essentially static, but the equations of general relativity did not seem to allow a time-independent solution for a universe with a uniform distribution of matter. So Einstein modified his equations, by including a new term involving a quantity that he called the cosmological constant. Then it was discovered that the universe is not static, but expanding. Einstein came to regret that he had needlessly mutilated his original theory. It may also have bothered him that he had missed predicting the expansion of the universe.

This story involves a tangle of mistakes, but not the one that Einstein thought he had made. First, I don't think that it can count against Einstein that he had assumed the universe is static. With rare exceptions, theorists have to take the world as it is presented to them by observers. The relatively low observed velocities of stars made it almost irresistible in 1917 to suppose that the universe is static. Thus when Willem de Sitter proposed an alternative solution to the Einstein equations in 1917, he took care to use coordinates for which the metric tensor is time-independent. However, the physical meaning of those coordinates is not transparent, and the realization that de Sitter's alternate cosmology was not static—that matter particles in his model would accelerate away from each other—was considered to be a drawback of the theory.

It is true that Vesto Melvin Slipher, while observing the spectra of spiral nebulae in the 1910s, had found a preponderance of redshifts, of the sort that would be produced in an expansion by the Doppler effect, but no one then knew what the spiral nebulae were; it was not until Edwin Hubble found faint Cepheid variables in the Andromeda Nebula in 1923 that it became clear that spiral nebulae were distant galaxies, clusters of stars far outside our own galaxy. I don't know if Einstein had heard of Slipher's redshifts by 1917, but in any case he knew very well about at least one other thing that could produce a redshift of spectral lines: a gravitational field. It should be acknowledged here that Arthur Eddington, who had learned about general relativity during World War I from de Sitter, did in 1923 interpret Slipher's redshifts as due to the expansion of the universe in the de Sitter model. (The two scientists are pictured with Einstein and others in figure 1.) Nevertheless, the expansion of the universe was not generally accepted until Hubble announced in 1929—and actually showed in 1931—that the redshifts of distant galaxies increase in proportion to their distance, as would be expected for a uniform expansion (see figure 2). Only then was much attention given to the expanding-universe models introduced in 1922 by Alexander Friedmann, in which no cosmological constant is needed. In 1917 it was quite reasonable for Einstein to assume that the universe is static.

Einstein did make a surprisingly trivial mistake in introducing the cosmological constant. Although that step made possible a time-independent solution of the Einstein field equations, the solution described a state of unstable equilibrium. The cosmological constant acts like a repulsive force that increases with distance, while the ordinary attractive force of gravitation decreases with distance. Although there is a critical mass density at which this repulsive force just balances the attractive force of gravitation, the balance is unstable; a slight expansion will increase the repulsive force and decrease the attractive force so that the expansion accelerates. It is hard to see how Einstein could have missed this elementary difficulty.

Einstein was also at first confused by an idea he had taken from the philosopher Ernst Mach: that the

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phenomenon of inertia is caused by distant masses. To keep inertia finite, Einstein in 1917 supposed that the universe must be finite, and so he assumed that its spatial geometry is that of a three-dimensional spherical surface. It was therefore a surprise to him that when test particles are introduced into the empty universe of de Sitter's model, they exhibit all the usual properties of inertia. In general relativity the masses of distant bodies are not the cause of inertia, though they do affect the choice of inertial frames. But that mistake was harmless. As Einstein pointed out in his 1917 paper, it was the assumption that the universe is static, not that it is finite, that had made a cosmological constant necessary.

Aesthetically motivated simplicity

Einstein made what from the perspective of today's theoretical physics is a deeper mistake in his dislike of the cosmological constant. In developing general relativity, he had relied not only on a simple physical principle—the principle of the equivalence of gravitation and inertia that he had developed from 1907 to 1911—but also on a sort of Occam's razor, that the equations of the theory should be not only consistent with this principle but also as simple as possible. In itself, the principle of equivalence would allow field equations of almost unlimited complexity. Einstein could have included terms in the equations involving four spacetime derivatives, or six spacetime derivatives, or any even number of spacetime derivatives, but he limited himself to second-order differential equations.

This could have been defended on practical grounds. Dimensional analysis shows that the terms in the field equations involving more than two spacetime derivatives would have to be accompanied by constant factors proportional to positive powers of some length. If this length was anything like the lengths encountered in elementary-particle physics, or even atomic physics, then the effects of these higher derivative terms would be quite negligible at the much larger scales at which all observations of gravitation are made. There is just one modification of Einstein's equations that could have observable effects: the introduction of a term involving no spacetime derivatives at all—that is, a cosmological constant.

But Einstein did not exclude terms with higher derivatives for this or for any other practical reason, but for an aesthetic reason: They were not needed, so why include them? And it was just this aesthetic judgment that led him to regret that he had ever introduced the cosmological constant.

Since Einstein's time, we have learned to distrust this sort of aesthetic criterion. Our experience in elementary-particle physics has taught us that any term in the field equations of physics that is allowed by fundamental principles is likely to be there in the equations. It is like the ant world in T. H. White's *The Once and Future King*: Everything that is not forbidden is compulsory. Indeed, as far as we have been able to do the calculations, quantum fluctuations by themselves would produce an infinite effective cosmological constant, so that to cancel the infinity there would have to be an infinite "bare" cosmological constant of the opposite sign in the field equations themselves. Occam's razor is a fine tool, but it should be applied to principles, not equations.

It may be that Einstein was influenced by the example of Maxwell's theory, which he had taught himself while a student at the Zürich Polytechnic Institute. James Clerk Maxwell of course invented his equations to account for the known phenomena of electricity and magnetism while preserving the principle of electric-charge conservation, and in Maxwell's formulation the field equations contain terms with only a minimum number of spacetime derivatives. Today we know that the equations governing electrodynamics contain terms with any number of spacetime derivatives, but these terms, like the higher-derivative terms in general relativity, have no observable consequences at macroscopic scales.

Astronomers in the decades following 1917 occasionally sought signs of a cosmological constant, but they only succeeded in setting an upper bound on the constant. That upper bound was vastly smaller than what would be expected from the contribution of quantum fluctuations, and many physicists and astronomers concluded from this that the constant must be zero. But despite our best efforts, no one could find a satisfactory physical principle that would require a vanishing cosmological constant.

Then in 1998, measurements of redshifts and distances of supernovae by the Supernova Cosmology Project and the High-*z* Supernova Search Team showed that the expansion of the universe is accelerating, as de Sitter had found in his model (see the article by Saul Perlmutter, PHYSICS TODAY, April 2003, page 53). As discussed in figure 3, it seems that about 70% of the energy density of the universe is a sort of "dark energy," filling all space. This was subsequently confirmed by observations of the angular size of anisotropies in the cosmic microwave background. The density of the dark energy is not varying rapidly as the universe expands, and if it is truly time-independent then it is just the effect that would be expected from a cosmological constant. However this works out, it is still puzzling why the cosmological constant is not as large as would be expected from calculations of quantum fluctuations. In recent years the question has become a major preoccupation of theoretical physicists. Regarding his introduction of the cosmological constant in 1917, Einstein's real mistake was that he thought it was a mistake.

A historian, reading the foregoing in a first draft of this article, commented that I might be accused of perpetrating Whig history. The term "Whig history" was coined in a 1931 lecture by the historian Herbert Butterfield. According to Butterfield, Whig historians believe that there is an unfolding logic in history, and they judge the past by the standards of the present. But it seems to me that, although Whiggery is to be avoided in political and social history (which is what concerned Butterfield), it has a certain value in the history of science. Our work in science is cumulative. We really do know more than our predecessors, and we can learn about the things that were not understood in their times by looking at the mistakes they made.

Contra quantum mechanics

The other mistake that is widely attributed to Einstein is that he was on the wrong side in his famous debate with Niels Bohr over quantum mechanics, starting at the Solvay Congress of 1927 and continuing into the 1930s. In brief, Bohr had presided over the formulation of a "Copenhagen interpretation" of quantum mechanics, in which it is only possible to calculate the probabilities of the various possible outcomes of experiments. Einstein rejected the notion that the laws of physics could deal with probabilities, famously decreeing that God does not play dice with the cosmos. But history gave its verdict against Einstein—quantum mechanics went on from success to success, leaving Einstein on the sidelines.

All this familiar story is true, but it leaves out an irony. Bohr's version of quantum mechanics was deeply flawed, but not for the reason Einstein thought. The Copenhagen interpretation describes what happens when an observer makes a measurement, but the observer and

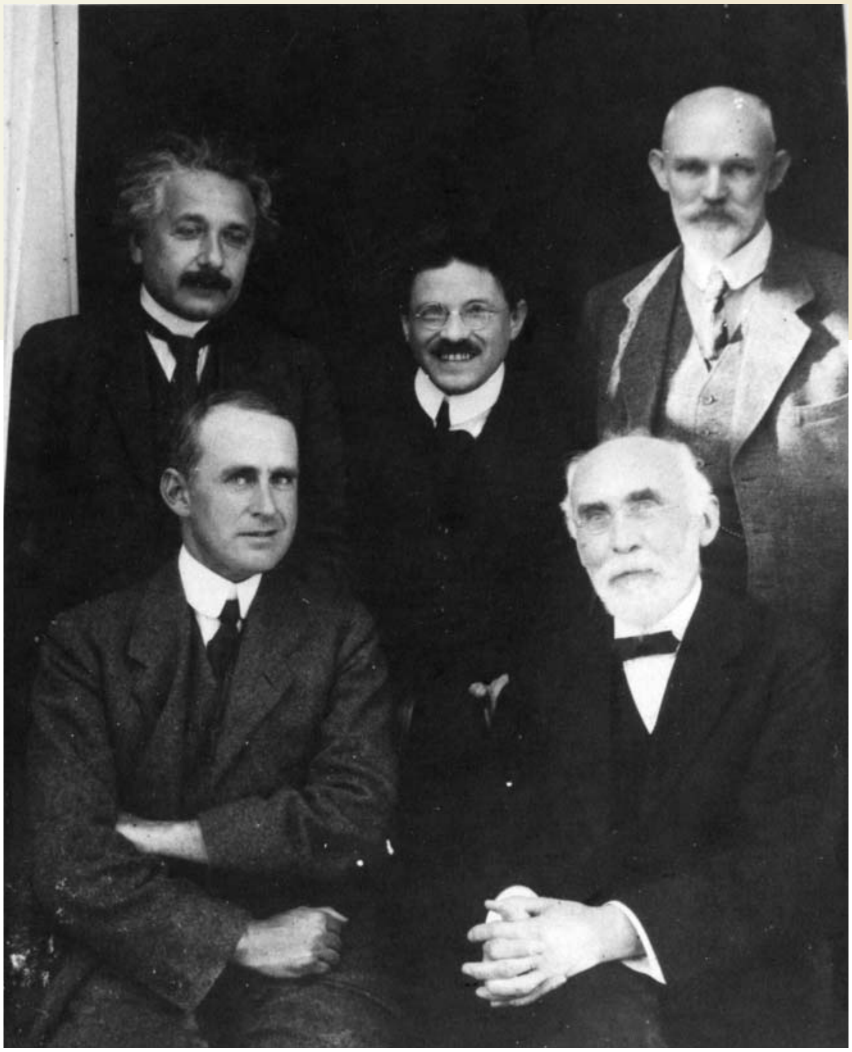

Figure 1. Albert Einstein (back left) poses with Willem de Sitter (back right), Arthur Eddington (front left), Hendrik Lorentz (front right), and Paul Ehrenfest (center) in this photograph taken at the Leiden Observatory, the Netherlands, in September 1923. (Courtesy of AIP Emilio Segrè Visual Archives.)

the act of measurement are themselves treated classically. This is surely wrong: Physicists and their apparatus must be governed by the same quantum mechanical rules that govern everything else in the universe. But these rules are expressed in terms of a wavefunction (or, more precisely, a state vector) that evolves in a perfectly deterministic way. So where do the probabilistic rules of the Copenhagen interpretation come from?

Considerable progress has been made in recent years toward the resolution of the problem, which I cannot go into here. It is enough to say that neither Bohr nor Einstein had focused on the real problem with quantum mechanics. The Copenhagen rules clearly work, so they have to be accepted. But this leaves the task of explaining them by applying the deterministic equation for the evolution of the wavefunction, the Schrödinger equation, to observers and their apparatus. The difficulty is not that quantum mechanics is probabilistic—that is something we apparently just have to live with. The real difficulty is that it is also deterministic, or more precisely, that it combines a probabilistic interpretation with deterministic dynamics.

Attempts at unification

Einstein's rejection of quantum mechanics contributed, in the years from the 1930s to his death in 1955, to his isolation from other research in physics, but there was another factor. Perhaps Einstein's greatest mistake was that he became the prisoner of his own successes. It is the most natural thing in the world, when one has scored great victories in the past, to try to go on to further victories by repeating the tactics that previously worked so well. Think of the advice given to Egypt's President Gamal Abd al-Nasser by an apocryphal Soviet military attaché at the time of the 1956 Suez crisis: "Withdraw your troops to the center of the country, and wait for winter."

And what physicist had scored greater victories than Einstein? After his tremendous success in finding an explanation of gravitation in the geometry of space and time, it was natural that he should try to bring other forces along with gravitation into a "unified field theory" based on geometrical principles. About other things going on in physics, he commented[3] in 1950 that "all attempts to obtain a deeper knowledge of the foundations of physics seem doomed to me unless the basic concepts are in accordance with general relativity from the beginning." Since electromagnetism was the only other force that in its macroscopic effects seemed to bear any resemblance to gravitation, it was the hope of a unification of gravitation and electromagnetism that drove Einstein in his later years.

I will mention only two of the many approaches taken by Einstein in this work. One was based on the idea of a fifth dimension, proposed in 1921 by Theodore Kaluza. Suppose you write the equations of general relativity in five rather than four spacetime dimensions, and arbitrarily assume that the 5D metric tensor does not depend on the fifth coordinate. Then it turns out that the part of the metric tensor that links the usual four spacetime dimensions with the fifth dimension satisfies the same field equation as the vector potential in the Maxwell theory of electromagnetism, and the part of the metric tensor that only links the usual four spacetime dimensions to each other satisfies the field equations of 4D general relativity.

The idea of an additional dimension became even more attractive in 1926, when Oskar Klein relaxed the

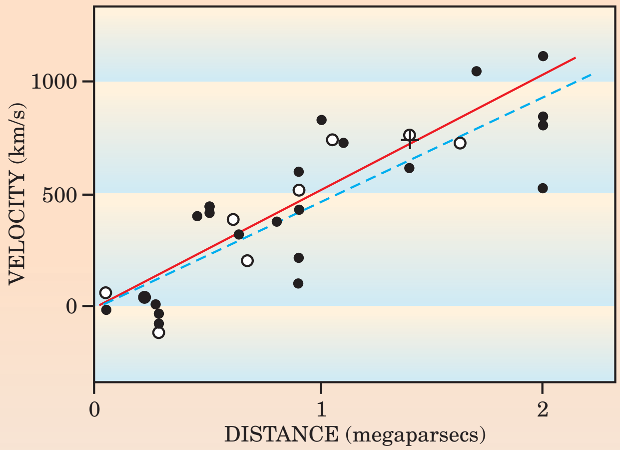

Figure 2. Recessional velocities of nearby galaxies vary linearly with distance as Edwin Hubble demonstrated in these data from 1929. The graph's filled circles and solid linear fit describe individual galaxies, open circles and the broken line correspond to galaxies combined into groups, and the cross represents the mean velocity and distance for a collection of 22 galaxies whose distances could not be individually estimated. A parsec is 3.26 light-years. Note that the slope of the graph, about 500 (km/s)/Mpc, is some seven times the now-accepted value. (Adapted from ref. 5.)

condition that the fields are independent of the fifth coordinate, and assumed instead that the fifth dimension is rolled up in a tiny circle so that the fields are periodic in that coordinate. Klein found that in this theory the part of the metric tensor that links the fifth dimension to itself behaves like the wavefunction of an electrically charged particle, so for a moment it seemed to Einstein that there was a chance that not only gravitation and electromagnetism but also matter would be governed by a unified geometrical theory. Alas, it turned out that if the electric charge of the particle is identified with the charge of the electron, then the particle's mass comes out too large by a factor of about 10^{18}.

It is a pity that Einstein gave up on the Kaluza–Klein idea. If he had extended it from five to six or more spacetime dimensions, he might have discovered the field theory constructed in 1954 by C. N. Yang and Robert Mills, and its generalizations, some of which later appeared as parts of our modern theories of strong, weak, and electromagnetic interactions.[4] Einstein apparently gave no thought to strong or weak nuclear forces, I suppose because they seem so different from gravitation and electromagnetism. Today we realize that the equations underlying all known forces aside from gravitation are actually quite similar, the difference in the phenomena arising from color trapping for strong interactions and spontaneous symmetry breaking for weak interactions. Even so, Einstein would still probably be unhappy with today's theories, because they are not unified with gravitation and because matter—electrons, quarks, and so on—still has to be put in by hand.

Even before Klein's work, Einstein had started on a different approach, based on a simple bit of counting. If you give up the condition that the 4×4 metric tensor should be symmetric, then it will have 16 rather than 10 independent components, and the extra 6 components will have the right properties to be identified with the electric and magnetic fields. Equivalently, one can assume that the metric is complex, but Hermitian. The trouble with this idea, as Einstein became painfully aware, is that there really is nothing in it that ties the 6 components of the electric and magnetic fields to the 10 components of the ordinary metric tensor that describes gravitation, other than that one is using the same letter of the alphabet for all these fields. A Lorentz transformation or any other coordinate transformation will convert electric or magnetic fields into mixtures of electric and magnetic fields, but no transformation mixes them with the gravitational field. This purely formal approach, unlike the Kaluza–Klein idea, has left no significant trace in current research. The faith in mathematics as a source of physical inspiration, which had served Einstein so well in his development of general relativity, was now betraying him.

Even though it was a mistake for Einstein to turn away from the exciting progress being made in the 1930s and 1940s by younger physicists, it revealed one admirable feature of his personality. Einstein never wanted to be a mandarin. He never tried to induce physicists in general to give up their work on nuclear and particle physics and follow his ideas. He never tried to fill professorships at the Institute for Advanced Studies with his collaborators or acolytes. Einstein was not only a great man, but a good one. His moral sense guided him in other matters: He

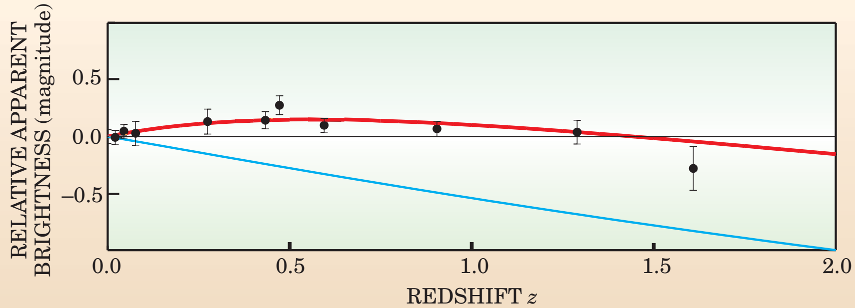

Figure 3. Measurements on distant supernovae show that the universe contains a preponderance of dark energy that behaves like a cosmological constant. Here the apparent brightness is a measure of distance, and the redshift a measure of recessional velocity. The brightness magnitudes are relative to those in an empty universe with no cosmological constant (black line). For the red curve that best fits the data, 70% of the cosmic energy density is attributed to a cosmological constant. A positive slope in a curve indicates cosmic acceleration; a negative slope corresponds to deceleration. The present-day universe is accelerating, but in an earlier epoch (high *z*) during which the universe was much smaller, the repulsive force associated with the cosmological constant was overwhelmed by matter's conventional gravitational attraction. The blue line, which assumes no cosmological constant, poorly fits the data. (Adapted from ref. 6.)

opposed militarism during World War I; he refused to support the Soviet Union in the Stalin years; he became an enthusiastic Zionist; he gave up his earlier pacifism when Europe was threatened by Nazi Germany, for instance urging the Belgians to rearm; and he publicly opposed McCarthyism. About these great public issues, Einstein made no mistakes.

References

1. The set of mistakes discussed in this article is not intended to be exhaustive. They are a selection, mostly chosen because they seemed to me to reveal something of the intellectual environment in which Einstein worked. In PHYSICS TODAY, March 2005, page 34, Alex Harvey and Engelbert Schucking have described an erroneous prediction of Einstein regarding the rates of clocks on Earth's surface, and in his book *Albert Einstein's Special Theory of Relativity*, Addison-Wesley, Reading, PA (1981), p. 328, Arthur I. Miller has discussed an error in Einstein's calculation of the electron's transverse mass.
2. G. Gamow, *My World Line—An Informal Autobiography*, Viking Press, New York (1970), p. 44. I thank Lawrence Krauss for this reference.
3. A. Einstein, *Sci. Am.*, April 1950, p. 13.
4. Oddly enough, at a conference in Warsaw in 1939, Klein presented something very like the Yang–Mills theory, on the basis of his five-dimensional generalization of general relativity. I have tried and failed to follow Klein's argument, and I do not believe his derivation makes sense; it takes at least two extra dimensions to get the Yang–Mills theory. It seems that scientists are often attracted to beautiful theories in the way that insects are attracted to flowers—not by logical deduction, but by something like a sense of smell.
5. E. Hubble, *Proc. Natl. Acad. Sci. USA* **15**, 168 (1929).
6. A. G. Riess et al., *Astrophys. J.* **607**, 665 (2004). ■