Name: _____ Date: _____

Testing Einstein: Eclipses, Airplanes, Satellites

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A theory in physics is worth what its tests are worth. In 1905 Albert Einstein was 26 and worked as a technical expert at the patent office in Bern. His papers made claims that were far ahead of any instrument. This book follows four tests of his ideas across 110 years. The first is a line of photoelectric data from 1916; the second is an eclipse in 1919; the third is a set of cesium clocks on airliners in 1971; the fourth is the atomic clocks in GPS satellites. For each test, it asks how large the effect was, how sure the measurers were, and who disagreed.

The desk matters, but less than legend says. In June 1902 Einstein got an answer to his application for a post as technical expert, class III, at the Federal Office for Intellectual Property. A month later he was judging inventions at a lectern in room 86. He called the job his "cobbler's trade." The office, which paid CHF 3,500 a year, says it was undemanding for his quick mind. A review in Physics Today notes that Bern began synchronizing its city clocks in 1890. Many patent applications for coordinating clocks by electric signals passed through the office. The record does not show which ones Einstein evaluated, and the reviewer finds the claim that this inspired relativity less than compelling.

Where do such ideas start? The main evidence is Einstein's own later accounts, decades old. In his Autobiographical Notes, published in 1949, he wrote that at four or five his father showed him a compass. He could "still remember – or at least believe I can remember" the deep impression it made. He also recalled a paradox he hit on at sixteen. If he chased a beam of light at speed c, he "should observe such a beam of light as an electromagnetic field at rest though spatially oscillating." Asked in 1953 whether such events shaped his work, he said he thought so, but that a person "has little insight into what goes on within him."

The 1905 papers were written in that spare time. The one Einstein signed in March was titled "On a Heuristic Point of View Concerning the Production and Transformation of Light." It proposed that light behaves like a gas of packets, called quanta. Each packet carries energy in proportion to its frequency. Physicist John Rigden, in Physics World, notes that no data in 1905 required light to be particulate. The best-known use of the idea was the photoelectric effect. Light shining on a metal frees electrons only above a threshold frequency. Wave theory said intensity should be what mattered. A quantum with too little energy cannot free an electron, however many quanta arrive.

This was the first test, and it was a straight line. Robert Millikan spent years on photoelectric measurements. His 1916 points, Rigden writes, "almost literally fell on top" of the line the quantum paper predicted. Millikan still called the light-particle hypothesis "bold, not to say reckless." Rigden adds that Planck and other physicists nominated Einstein to the Prussian

Academy in 1913. As Rigden renders it, they wrote that he sometimes went too far in his guesses, light quanta among them. Arthur Compton showed in 1923 that light quanta carry momentum. The Nobel Foundation cites Einstein's "discovery of the law of the photoelectric effect" for the 1921 prize, which was given in 1922. The citation does not mention relativity, the work for which he is better known.

Special relativity came in a paper dated June 30, 1905. It rests on two postulates. The laws of physics are the same in every frame moving steadily, and light in empty space travels at a speed c that does not depend on the source. Today c is exact, at 299,792,458 meters per second, and it defines the meter. The paper predicts that a clock carried from A to B lags a clock that stayed. A second paper, dated September 27, concluded that the mass of a body measures its energy-content. If a body radiates energy L, its mass falls by L/c². Since c² is about 9 × 10¹? in meters squared per second squared, a kilogram corresponds to roughly 9 × 10¹? joules. Einstein suggested testing the idea with radium salts.

Gravity took longer. In 1907, Einstein later wrote, "the happiest thought of my life" came to him. An observer falling freely from a roof has, for the length of the fall, no gravitational field in the immediate vicinity. Over the next years he left the patent office, in the autumn of 1909, for posts in Zurich, Prague, Zurich again and Berlin. On November 25, 1915, he presented the final form of general relativity to the Prussian Academy of Sciences. In it, gravity is the curving of space and time, and that makes a prediction about light that can be checked. For starlight grazing the Sun, it predicts a deflection of 1.75 arcseconds. That is 1.75/3,600 of a degree, while Newton's theory gives half as much, 0.875 arcseconds.

The second test needed an eclipse, because only then can stars beside the Sun be photographed. On May 29, 1919, one British party stood at Principe, an island off West Africa. Another stood at Sobral, in Brazil. Each team compared plates exposed during totality with plates of the same star field taken at night. The night plates were taken months earlier or later by the same telescope. Sobral had mostly clear sky, but at Principe thick cloud left only two satisfactory plates. Gilmore and Tausch-Pebody describe the method in a 2020 paper in the Royal Society's Notes and Records. The astronomers analyze small differences in the relative position of each star image between the two photographs.

The numbers, in arcseconds with probable errors, were these. The Sobral 4-inch telescope gave 1.98 ± 0.12. Principe gave 1.61 ± 0.30. Einstein's 1.75 falls between them, and the older Newtonian value, 0.875, lies below both. A third set, from a second Sobral telescope, had a formal result of 0.93, which the report called discordant. It was set aside because its images were out of focus. The results were announced to a joint meeting of two scientific societies in London on November 6, 1919. Einstein became world famous on November 7, after the press reported it. Gilmore and Tausch-Pebody call the Sobral 4-inch result the most precise of the three, and the 1919 report said plainly that the Principe result carried large uncertainty from possible systematic errors.

The discarded set became an argument. In 1980 the philosophers Earman and Glymour claimed that the choice of data was flawed. Gilmore and Tausch-Pebody reanalyzed the 1919 data in 2020, and they say they identified the error that undermines that claim. NASA's Hubble pages note that some astronomers questioned the equipment, but that many observations since have confirmed the deflection. Those include gravitational lenses, where a cluster of galaxies bends light from behind it. NASA describes one cluster 5 billion light-years away. It split the light of a distant exploding star into four images, called an Einstein Cross. The argument over 1919 shows that a choice about which measurements to trust can weigh as much as the measurements themselves.

The third test put clocks on aircraft. In October 1971, Joseph Hafele and Richard Keating flew four cesium clocks twice around the world on scheduled jets, once east and once west. They then compared the clocks with those at the US Naval Observatory. The clocks that flew east moved faster than the ground beneath them, and all the flying clocks spent their time in weaker gravity. HyperPhysics prints a table from their 1972 paper in Science. The eastward clocks were predicted to lose 40 ± 23 nanoseconds and lost 59 ± 10. The westward clocks were predicted to gain 275 ± 21 nanoseconds, and they gained 273 ± 7. NIST says the results agreed with both special and general relativity to within the margin of error.

The fourth test is under your phone. GPS satellites fly at about 20,200 kilometers and circle the Earth twice a day. The United States commits to keeping at least 24 operating. NIST writes that special relativity says their clocks should fall behind ground clocks by 7 microseconds a day. Weaker gravity should speed them up by 45, for a net of 38 microseconds a day faster. An Ohio State astronomy page notes that this is 38,000 nanoseconds, in a system that needs clock timing to 20 to 30 nanoseconds. NIST says the signals would quickly be useless without correction. It calls GPS the longest-running test we have of Einstein's theories.

Einstein died in Princeton, New Jersey, on April 18, 1955, but the tests did not stop. NIST reports that in 2014 two Galileo satellites were put in elliptical orbits by mistake. Two groups used their clocks to confirm general relativity 5.6 times more precisely than the best earlier result. In 2019 a team led by Hidetoshi Katori found that a clock at the top of the Tokyo Skytree ran four nanoseconds a day fast. As of NIST's February 2026 article, two more tests were under way. One compares clocks more than 2,500 meters apart in height on a Colorado mountain. The other uses clocks on the International Space Station. No results were reported. If predictions about gravity and time proved even slightly off, NIST says, the discrepancy could upend our theories about the universe.

Questions

1. Why did Millikan's 1916 data matter for Einstein's light-quantum paper?

A. They disproved the idea entirely
B. They were collected during an eclipse
C. Their points fell near the predicted line

2. Why was one 1919 data set set aside?

A. It showed no stars
B. Its images were out of focus
C. It was taken in daylight

3. What does the Physics Today review suggest about the claim that clock-synchronizing patents inspired relativity?

A. It was proven by Einstein's own notes
B. The record does not show which patents he judged
C. It was confirmed by every historian

4. In "the margin of error," what does margin mean?

A. A range of uncertainty
B. A page edge
C. A profit

5. By NIST's count, how much faster per day do GPS satellite clocks run than clocks on the ground?

A. 45 microseconds
B. 7 microseconds
C. 38 microseconds

Words to know

quanta: energy packets
frequency: waves per second
deflection: bending away
probable: likely
nanoseconds: billionths of seconds

Answer key: Testing Einstein: Eclipses, Airplanes, Satellites

1. C. Their points fell near the predicted line
2. B. Its images were out of focus
3. B. The record does not show which patents he judged
4. A. A range of uncertainty
5. C. 38 microseconds