Einstein's *annus mirabilis*

One hundred years ago, Einstein published five papers that led to revolutionary changes in our understanding of the properties of space, time and the microscopic world.

As a student, Einstein said, he had no feeling for the important problems in mathematics, whereas in physics he always had a sense of what is really significant. He certainly proved this in 1905. In that miraculous year he: 1) made major contributions to the classical kinetic theory of atoms and molecules; 2) resolved the apparent conflict between classical mechanics and the optics and electrodynamics of moving bodies; and 3) laid the foundations for the quantum theory of light.

Kinetic Theory: To this day, Einstein's two papers on molecular behavior and Brownian motion (the random jostling of small particles, like dust in water) are cited more often than his other 1905 papers because of the many practical applications of his formulas for diffusion and viscosity. The paper on Brownian motion is also of great theoretical interest because it is the first successful mathematical treatment of a stochastic (random) process.

Relativity: People like Lorentz and Poincaré were trying to understand why experimental attempts to observe a background "ether," assumed to pervade space, had failed. Einstein realized that, since the days of Fresnel and Fizeau, such experiments had been trying to tell us that the traditional way of understanding motion break down for speeds approaching that of light. What was needed was to replace the old mechanics, in which the time was absolute, with a new mechanics, in which the speed of light is absolute and space and time behave differently from the perspective of observers in different states of motion.

It took years before this new viewpoint prevailed. Indeed, a look at some current textbooks' treatment of the special theory shows that it still has not prevailed everywhere.

Quantum theory: The only 1905 paper Einstein described as "revolutionary" is the one on quantum theory, which introduced the idea that there are smallest possible elements (quanta) of light. This work on the photoelectric effect won the Nobel prize in 1921. In contrast to attempts by Planck and others to patch up classical theories in order to incorporate quantum phenomena, Einstein proclaimed from the start that neither classical mechanics nor classical electrodynamics would survive the quantum revolution. His concept of light quanta was widely derided until the discovery of the Compton effect (involving the scattering of light by electrons) in 1923 made clear the need for a quantum theory of light.

On the other hand, Einstein's explanation in 1907 of certain puzzling thermal properties of crystalline solids—treating the crystal's molecules as quantum oscillators—convinced most physicists of the need for a quantum theory of matter, making quantum theory a major research topic even before Bohr's 1913 theory of the hydrogen atom.

By 1907, Einstein was at work on an extension of relativity theory to include gravitation. He soon realized that gravity and inertia are two sides of the same coin and their equivalence is the key to understanding gravity. This insight implies that inertial (non-accelerating) frames of reference, which had maintained their privileged status in the special theory of relativity, must be dethroned. To include gravitation, his 1905 theory had to give way to a generalized theory of relativity, with no privileged frames of reference. Most physicists scoffed and continued to seek ways to incorporate gravitation with special relativity—indeed, many still do!

However, Einstein persevered, and by 1915 had developed a theory of gravity in which all space-time structures are dynamical objects, in bold contrast to all other physical theories, including the quantum theories developed later. These all depend on some fixed background space-time structures, and hence are called background-dependent theories.

Attempts to create a quantum theory of gravity must somehow reconcile general relativity with quantum mechanics. They face this dilemma: Is it possible to formulate a background-independent quantum gravity theory, as general relativity suggests? Or must we give up background independence in order to quantize gravity as quantum theory suggests? Most physicists—including string theorists—believe in the latter alternative. But if the former proves possible and the resulting theory is physically fruitful—as loop quantum gravity advocates have shown there is reason to hope—then the formulation of the first background-independent physical theory will surely rank as Einstein's greatest achievement.

John Stachel

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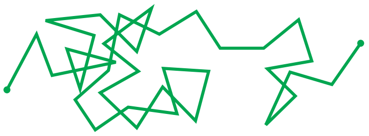
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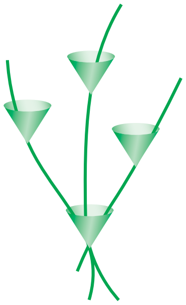
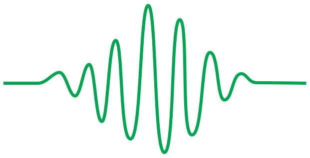

Special Relativity


Quantum Physics

The death of common sense

Prior to the development of special relativity, the laws of physics and the laws of common sense were practically one and the same. Measurements of space and time were absolute. There were no limits in principle on how fast a person could travel. A meter was a meter and a second was a second no matter what.

The birth of Albert Einstein's theory 100 years ago marked the death of these common-sense notions of space, time, and travel. According to Einstein, measurements of time and length intervals differ when made by observers who are moving relative to each other. There is no universal time. Nothing can travel faster than the speed of light. Einstein also deduced that mass is a form of energy, expressed by the famous equation $E=mc^2$.

As is often the case with revolutionary new theories, the theory of relativity emerged from a crisis in the physics community: How does light travel? The prevailing view before Einstein was that light waves traveled through an all-pervasive medium called the ether. The speed of light was defined with respect to the rest frame of the ether.

Albert Michelson's experiments, however, failed to detect Earth's motion through the ether. Without this medium, what could serve as the reference frame for light rays traveling through empty space?

Einstein proposed the radical idea that light in a vacuum always travels at the same constant speed, c (roughly 300,000 km/s). No matter how fast an observer travels relative to a light source, the emitted light always travels at the same speed, c. There was no need for an ether.

Einstein believed that any observer moving at constant velocity (in a so-called inertial frame) experiences the same laws of physics. If nothing distinguishes one inertial frame from another, then the speed of light would naturally be the same in all such frames.

Einstein's radical theory ultimately gained acceptance, and now pervades all modern physics. Special relativity is an essential component in the Standard Model (SM) of particle interactions. The lifetimes of fast-moving unstable particles vary with their relative speed precisely as predicted by relativity. $E=mc^2$ is confirmed every time a particle and antiparticle annihilate to produce light.

But the Standard Model completely ignores the gravitational interaction. The SM is a quantum theory, and there is no known completely viable quantum theory of gravity (there are candidate models, such as string theory). Most physicists believe that, ultimately, a unified fundamental theory will merge a quantum theory of gravity with the SM.

Whether Einstein's theory of relativity would then remain intact is unclear. Some researchers are looking for violations of relativity as a signature of quantum-gravity effects. A general theory (called the Standard Model Extension or SME) developed by Alan Kostelecký and coworkers at Indiana University has been used to search for relativity violations in particle, atomic, and astrophysical experiments.

One of the best tests of relativity theory—sensitive to an extremely delicate particle-antiparticle balancing act in kaons—has been conducted by the KTeV collaboration at the Fermilab Tevatron. KTeV tested interactions in the SME that would cause relativity violations to the level of parts in 10^{21}. The BaBar experiment at SLAC conducts similar searches using B mesons.

So far, Einstein can rest easy—no violations of relativity have been found. However, increasingly-precise experiments will probe further into the realm where quantum-gravity effects are expected to appear. If they find violations of relativity, they would signal the beginning a new revolutionary period in physics as great as the one Einstein began 100 years ago.

Robert Bluhm

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