Einstein in the 21st century

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(1) 1905 the "Miraculous Year"

(a) Photo electric effect

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

(b) Brownian Motion

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

(c) Special Theory of Relativity

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

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

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

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

(2) General Theory of Relativity

"I have just completed the most splendid work of my life..."
--to his son Hans Albert, 1915

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

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

Success in his theoretical work was sealed in 1915. The new equations of gravitation had an essential logical simplicity, despite their unfamiliar mathematical form. To describe the action of gravity, the equations showed how the presence of matter warped the very framework of space and time. This warping would determine how an object moved. Einstein tested his theory by correctly calculating a small discrepancy in the motion of the planet Mercury, a discrepancy that astronomers had long been at a loss to explain Einstein's new general theory of relativity predicted a remarkable effect: when a ray of light passes near a massive body, the ray should be bent. For example, starlight passing near the sun should be slightly deflected by gravity. This deflection could be measured when the sun's own light was blocked during an eclipse. Einstein predicted a specific amount of deflection, and the prediction spurred British astronomers to try to observe a total eclipse in May 1919. Feverish preparations began as the war ended. Two expeditions, one to an island off West Africa and the other to Brazil, succeeded in photographing stars near the eclipsed sun. The starlight had been deflected just as Einstein had predicted.

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

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

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

(3) Bose – Einstein Statistics

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

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

(4) Unification of Fundamental Forces

From before 1920 until his death in 1955, Einstein struggled to find laws of physics far more general than any known before. In his theory of relativity, the force of gravity had become an expression of the geometry of space and time. The other forces in nature, above all the force of electromagnetism, had not been described in such terms. But it seemed likely to Einstein that electromagnetism and gravity could both be explained as aspects of some broader mathematical structure. The quest for such an explanation -- for a "unified field" theory that would unite electromagnetism and gravity, space and time, all together -- occupied more of Einstein's years than any other activity.
Einstein thought that if only he could find the right unified field theory, that theory might also explain the structure of matter. Thus he could fill the troubling gap in quantum theory -- the inability to describe the world otherwise than in terms of mere probabilities. He doubted his ability to find this "more complete theory," but he was convinced that someday, somebody would find it. "I cannot," he admitted, "base this conviction on logical reasons -- my only witness is the pricking of my little finger."

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

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