One hundred years since Albert Einstein's annus mirabilis

Part 3

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This is the third part of a four-part series on Einstein's scientific contributions. Part one was published on July 11 and part two on July 12. Part four will be published on July 14.

Einstein was, however, influenced by Mach's critique of Newtonian mechanics, which centred on the assumption of an absolute frame of reference—an absolute time and space. The necessity for a frame of reference arises from the nature of motion itself: an object is said to be moving with respect to something else. To measure speed requires a determination of distance travelled and time taken. Both measurements require not only measuring devices, but a starting point—a time zero and a position from which to measure distance. Newton postulated an absolute time and absolute space as the basic reference for all motion.

Newton's absolute frame of reference was also needed to determine the character of the movement. Simple laws apply to constant motion in a straight line (an inertial frame of reference). More complex considerations are involved in analysing non-inertial systems—those involving acceleration, that is changes of speed or direction. How could one tell if an object was spinning, speeding up or slowing down without an absolute frame of reference against which to judge it?

Newtonian mechanics had its own principle of relativity: for all inertial systems, the laws of motion are the same. Anyone who has sat in a railway carriage, and watched a neighbouring train pull out, has an inkling of what this means. There is a moment of discomfort as the brain works out: is my train moving, or is the other one? Then reassuring signs click in: the platform is not moving, the carriage is not bumping. But suppose the train in which you are sitting has blackened windows and rests on completely smooth tracks. How would you tell if you were moving or not? The principle of relativity explains that there is no test or experiment that can determine whether the carriage is moving (at constant speed) or at rest.

If that were the case, Mach argued, then what was the meaning of Newton's absolute time and space. Absolute space was a "monstrous conception", he declared. Motion was relative, not absolute. In a debate with Leibniz, Newton had used the motion of water in a spinning bucket as evidence of the existence of an absolute frame of reference. Mach insisted that the spinning of water in Newton's bucket only had any meaning against the background of the universe—the stars in the sky.

When it came to laws of electromagnetism, however, matters appeared to be different. Maxwell's equations provided a remarkable correspondence between the speed of electromagnetic waves and the speed of light, but left an obvious question unanswered: what was the frame of reference for measuring the speed of light? The postulation of a fixed ether appeared to provide a solution. The speed of light was measured with respect to the ether, which also provided a physical basis for absolute space and time.

But the assumption of a fixed ether meant that the principle of relativity did not apply to the laws of electromagnetism. As Einstein explained in the opening of his 1905 paper on special relativity, there were dissatisfying "assymmetries". He gave a simple example of a coil and a magnet: as Faraday discovered, if one moves relative to the other, then an electric current results. It should not matter whether it is the magnet or the coil that moves. But according to the electrodynamics of the day, a different equation was required depending on whether the coil or the magnet moved in relation to the ether.

All of the efforts to resolve the contradiction between Newtonian mechanics and Maxwell's equations had assumed that it was the laws of electromagnetism, elaborated less than half a century before, that required further modification and refinement. Lorentz had been forced to make a long list of assumptions to produce his version of electrodynamics that failed to explain the Michelson-Morley result and maintained the unpleasant "assymmetries".

Einstein's approach was based on the audacious assumption that it was Newtonian mechanics that required modification, not the laws of electromagnetism. His paper on special relativity hinged on just two basic premises. The first was that the principle of relativity applied not only to Newton's laws but to Maxwell's equations as well—an assumption that at one stroke abolished Lorentz's list of special conditions. The second was that the speed of light is constant, regardless of the speed of the source of light or speed of the light detector.

This second premise involved a fundamental revision of Newtonian mechanics. How could the speed of light be the same regardless of the speed of the observer? Using the analogy of a car and a train, it amounted to saying that no matter how fast a car travelled, the relative speed of the train remained the same. In other words, one could never catch up to, let alone overtake, the train. What appears absurd when applied to cars and trains was exactly what Einstein assumed to be the case with light: it was impossible to ever catch up to a beam of light.

This assumption was completely in line with the spirit of Maxwell's equations, which determined the speed of light but provided no frame of reference. It also solved the riddle of the Michelson-Morley experiment, as the relative movement of the earth and the ether no longer made any difference to the speed of light. No matter how one raced the two beams of light, their speeds were always identical. In fact, the ether that had been hypothesised to provide a frame of reference to measure the speed of light was no longer needed.

Einstein's two premises appeared irreconcilable. To square them, he had to modify the basic conception of time. To declare two events to be simultaneous required an instrument for measuring time—clocks—and a method of synchronising them. But if one used light to synchronise clocks between two frames of reference moving relative to one another, then the light beam took a finite amount of time to travel between the two and the result would be differing "local times". To an observer examining the clock in the other frame of reference, time appeared to slow.

As Einstein worked out the consequences of his assumptions, he also accounted for the Lorentz-Fitzgerald contraction. An object travelling at high speed with respect to an observer would appear to contract. Moreover, masses would appear to get heavier as they travelled faster. Consideration of this last point led Einstein to write a further short paper in September 1905. It declared that energy (E) and mass (m) could no longer be considered independently, but were interchangeable according to the famous equation E=mc2, where c is the speed of light in a vacuum.

The reaction to relativity theory

Einstein's genius did not reside in lengthy, intricate arguments or complex mathematics. His paper on special relativity took up just 30 pages in *Annalen der Physik* and the mathematics goes not much beyond senior high school level. Nevertheless, it involved the adoption of an entirely new standpoint. Einstein concluded that to resolve the contradictions plaguing physics required two entirely novel premises, and he did not resile from their apparently strange consequences.

As one author explained: "Indeed, the whole [1905] paper is a testament to the power of simple language to convey deep and powerfully disturbing ideas. Reading it is like following the writer, Albert, into a deceptively straightforward-looking maze, taking one obvious, even boring, step after another, until all of a sudden you are standing on your head and there is no way home." [14]

In 1908, one of Einstein's mathematics lecturers, Hermann Minkowski, presented relativity theory in geometric form—in the four-dimensional geometry of space and time. In this rather unusual world of space-time, space and time are no longer independent but depend on relative speed. As the object begins to move in space, as Einstein showed, time slows. While space and time were shown to be relative, space-time provided a new absolute frame of reference.

Einstein's 1905 paper was not the end, but just the beginning. Special relativity only applied to objects travelling at constant speed, that is, to inertial frames of reference. To extend relativity theory to accelerating or non-inertial frames of reference also involved accounting for gravitational forces. Newton regarded gravity as a force that acted instantaneously at a distance. According to the theory of relativity, however, nothing travelled faster than the speed of light. While wrestling with the problem of general relativity, Einstein described his 1905 paper as "child's play" in comparison.

Nevertheless, while the mathematics is considerably more complex, at the heart of general relativity theory were some elegant and simple conceptions. The most fundamental was the equivalence of gravitational and inertial forces—in essence, that there is no difference between the earth's gravity and the artificial "gravity" experienced by an astronaut inside a spinning space station. By developing this basic idea, Einstein came to an astonishing conclusion: that massive objects warped space-time and that gravity was a consequence of this warping. He not only accounted for gravity in his general theory but for the first time offered what had eluded Newton: an explanation of the underlying causes. The general theory was only finally completed in 1915.

Relativity theory represented a sharp and fundamental break with Newtonian mechanics, as well as its continuation. At velocities that are small relative to the speed of light (300,000 km per second), the motions of objects can be accurately predicted by Newton's laws. But as velocities near the speed of light—in today's huge machines for accelerating subatomic particles, for example—that is no longer the case.

Imbued with a deep appreciation of the entire history of science, Einstein regarded the theory of relativity as the inevitable consequence of the challenge posed to Newtonian mechanics by electromagnetic theory. With the benefit of hindsight, some commentators belittle his achievements, declaring that if he had not formulated relativity theory, someone else would have. A few have denied Einstein's achievements altogether, absurdly claiming that his 1905 paper was plagiarised from Poincaré and others, or was really the work of his first wife, Mileva Maric.

Fellow physicist John Wheeler answered rather eloquently: "Historians of science can tell us that if Einstein had not come to this version of spacetime it would have been achieved by Lorentz, or Poincaré, or another, who would have come eventually to that famous equation E=mc2, with all its consequences. But it still comes to us as a miracle that the patent office clerk was the one to deduce this greatest of lessons about spacetime from clues on the surface so innocent as those afforded by electricity and magnetism. Miracle? Would it not have been a greater miracle if anyone but a patent office clerk had discovered relativity? Who else could have distilled this simple central point from all the clutter of electromagnetism than someone whose job it was over and over each day to extract simplicity out of complexity? If others could have given us special relativity, who else but Einstein... could have given us general relativity?" [15]

One of the clearest indications of the magnitude of Einstein's accomplishment came in the response to his 1905 paper. As his sister Maja explained: "The young scholar imagined that his publication in the renowned and much-read journal [*Annalen der Physik*] would draw immediate attention. He expected sharp opposition and the severest criticism. But he was very disappointed. His publication was followed by icy silence. The next few issues of the journal did not mention his paper at all. The professional circles took an attitude of wait and see." [16]

The first specific response did not come until 1906, when the prominent experimental physicist Walter Kaufman produced data that contradicted Einstein's predictions about the motion of electrons. Confident in the theoretical integrity of his work, Einstein called for "a more diverse body of observations" before his theory was rejected. It was only in 1916 that the flaws in Kaufmann's procedures were detected. The corrected results confirmed that special relativity accurately described the behaviour of fast-moving electrons.

Among the older generation of physicists, there was a distinct resistance to Einstein's conclusions. Right up to his death in 1912, Poincaré, who perhaps came closest to formulating a theory of relativity, studiously ignored the young man and his work. Mach, who had initially embraced relativity theory as a confirmation of his philosophical views, "cancelled" this position in a 1913 preface, declaring "present-day relativity" was "growing more and more dogmatical". Lorentz expressed his uneasiness in a lecture in 1913, declaring: "As far as this lecturer is concerned, he finds a certain satisfaction in the older interpretations, according to which the ether possesses at least some substantiality, space and time can be sharply separated, and simultaneity without further reservations can be spoken of." [17]

These reservations were evident in the deliberations of the Nobel Prize committee. It was not until 1922 that the committee decided to award Einstein the Nobel Prize for physics. By then, his relativity theory had been recognised and widely deployed by a new generation of physicists. In 1919, the astronomer Arthur Eddington provided the first observational evidence that light from distant stars was bent by the gravity of the Sun—an effect predicted by general relativity. Einstein was not, however, given the physics prize for his relativity theory, with which a majority of the Nobel physics committee still disagreed. It was awarded for his paper on the quantum theory of light—more specifically for a particular application to the photoelectric effect. And there was an additional proviso: that the recipient refrain from mentioning his theory of relativity in his Nobel lecture. If not for the King of Sweden, who was in the audience and wanted to hear about the theory, Einstein would have been forced into silence on his best-known, and most significant, achievement.

To be continued

Notes:

14. *Einstein in Love—A Scientific Romance*, Dennis Overbye, Viking Penguin, 2000, p. 135
15. Wheeler, op cit, p.570
16. Quoted in Rigden, op cit, p.96
17. Ibid, p.102-3