One hundred years since Albert Einstein's annus mirabilis

Part 4

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This is the conclusion of a four-part series on Einstein's scientific contributions. Part one, part two, *and* part three *were published on July 11, 12 and 13, respectively.*

Any consideration of Einstein's subsequent scientific career necessitates an examination, at least in brief, of the other strand of modern physics that he helped to initiate in 1905—quantum mechanics. It was no accident that the Nobel Prize committee focussed on the photoelectric effect, rather than the quantum theory of light—which Einstein had considered "truly revolutionary". Most scientists found it difficult to accept that light could behave both as a wave and a particle. How, after all, was it possible that anything could be continuous and spread out like a wave, and at the same time be discontinuous and localised like a particle?

The response of experimental physicist Robert Millikan to his own results in 1914, confirming Einstein's predictions for the photoelectric effect, summed up the prevailing attitude. "We are confronted... by the astonishing situation that these facts were correctly and exactly predicted nine years earlier by a form of quantum theory which has now been pretty much abandoned." [18] Yet as investigations of the atom proceeded, the dual wave-particle character of nature was found to be all-pervasive. Just as light could also be considered as a particle, so subatomic particles had to be treated as waves, if their behaviour was to be explained.

J.J. Thomson proposed the so-called plum pudding model of the atom—a blend of equal numbers of negatively charged electrons and positively charged particles. Elementary physics tells us that positive and negative charges attract. According to Thomson, the equal numbers of positive and negative cancelled each other out, leaving the atom electrically neutral. In 1912, however, Ernest Rutherford made the startling discovery that the atom was largely space—that the electrons moved in orbits around a small, heavy, positively charged nucleus.

This model of the atom—electrons whizzing around a compact nucleus—is so commonly accepted today that it is immediately recognisable. But at the beginning of the twentieth century, it threw up disturbing questions. If the electrons were orbiting around a positive nucleus, what prevented them from gradually spiralling in towards the nucleus? And if they did spiral in, electrons would emit electromagnetic radiation, including light, across a continuous range of frequencies. Energised atoms, however, were found to emit light only at specific frequencies—in other words, their observed spectra were not the full rainbow of colours, but a series of sharp, separated lines.

The nucleus also posed a dilemma. If it consisted of positively charged particles—protons—what held it together? After all, as school science teaches, like charges repel. Gravity was far too weak to provide the answer. There had to be other, unknown, nuclear forces at work. In fact, there turned out to be two—the strong and the weak—as well as a veritable zoo of other nuclear particles. The first, identified by James Chadwick in 1932, was the neutron—an electrically neutral particle, slightly more massive than the proton.

But it was the problem of the orbiting electrons that led directly to quantum mechanics. In a series of papers in 1913, Niels Bohr proposed that electrons could not move in arbitrary paths around the nucleus, but were constrained to a number of fixed orbits. They did not spiral, but instantaneously "jumped" from one orbit to another. To jump from a lower to a higher energy level, the electron had to receive a lump or quantum of energy of a fixed size. To drop from a higher to a lower, it emitted a quantum of energy. The energy of the quantum was, according to Planck and Einstein, directly related to its frequency. Thus, the theory explained the observed spectra: electron "jumps" produced only particular frequencies of light—that is, sharp spectral lines.

Bohr's theory was rather makeshift and limited. It applied only to an atom with one electron and one proton—a hydrogen atom—and did not, even then, account for a number of its properties. A radically different proposal, which incorporated Bohr's ideas, was made by Louis de Broglie in 1924. He suggested that the various energy levels could be accounted for by considering the electron, not as a discrete particle, but as a wave, loosely speaking spread out around the orbit. Instead of being an arbitrary assumption, Bohr's energy levels could be derived from the wavelength of the de Broglie wave. Einstein pointed out that if de Broglie were correct, then electrons should exhibit wave-like properties—such as diffraction—a property that was demonstrated in 1927 by Clinton Davisson and Lester Germer.

De Broglie's proposal, however, begged the obvious question: waves of what? Erwin Schrödinger first suggested that the waves were "smeared out" electrons, but no experimental evidence exists of fractional bits of electrons. In 1926, Max Born put forward the radical idea that remains, today, at the heart of quantum mechanics: that the "electron waves" could be interpreted as "probability waves". The "peaks" of the wave corresponded to the places with a high probability of finding an electron; the "troughs" to regions where there was a low probability of finding an electron.

In 1926, Schrödinger and, independently, Werner Heisenberg, formulated a comprehensive theory of quantum mechanics that centrally incorporated Born's idea. The following year, Heisenberg formulated his "uncertainty principle" developed from the paradoxical wave-particle duality of matter: that there existed an absolute limit to our ability to measure simultaneously certain pairs of properties. For instance, it was not possible to determine exactly the instantaneous position and speed of an electron. As Heisenberg explained: "We *cannot* know, as a matter of principle, the present in all its details." [19]

Probability and the universe

Physicist Brian Greene commented: "This is a truly peculiar idea. What business does probability have in the formulation of fundamental physics? We are accustomed to probability showing up in horse races, in coin tosses, and at the roulette table, but in those cases it merely reflects our *incomplete knowledge*." In the case of a roulette wheel, Greene explained, it is conceivable, given enough information and sufficiently powerful computers, to use Newtonian mechanics to calculate exactly where the roulette ball will land. "We see that probability as encountered at the roulette table does not reflect anything particularly fundamental about how the world works. Quantum mechanics, on the contrary, injects the concept of probability into the universe at a far deeper level. According to Born and more than half a century of subsequent experiments, the wave nature of matter implies that matter itself must be described fundamentally in a probabilistic manner." [20]

In the case of macroscopic objects like roulette wheels and balls, their wave-like character is insignificant and Newtonian mechanics remains a highly accurate approximation. But at the subatomic level, quantum mechanics has proven to be an indispensable tool in predicting often strange processes. Its underlying assumptions, however, are, as Greene pointed out, deeply unsettling. Einstein, for one, was concerned that quantum mechanics undermined causation: physics could no longer determine exact outcomes, only the probability of different outcomes.

In the course of the late 1920s and 1930s, Einstein and Bohr debated the meaning of the widely recognised Copenhagen interpretation of quantum mechanics, for which Bohr was responsible. Central to the Copenhagen interpretation was the Heisenberg uncertainty principle and Bohr's associated notion of complementarity—essentially that the contradictory wave-particle nature of matter had to be accepted as fundamental. He insisted that a phenomenon could not be considered apart from the apparatus required to observe or measure it. Bohr's interpretation veered in the direction of dispensing with objective reality altogether, and has certainly been seized on by various philosophical idealists as a vindication of their outlook.

In the course of the debate, Schrödinger, who sided with Einstein, posed a thought experiment that elevated the issues from the rather obscure world of subatomic particles to macroscopic, everyday objects. What if, Schrödinger asked, a live cat were placed in a box with a phial of poison and a trigger device based on the decay of a radioactive substance. At a certain time, quantum mechanics tells us that there is a 50:50 chance that the trigger has been activated and the poison released. If we open the box at that time, the cat will either be dead or alive. But what about just before we open the box? According to the Copenhagen interpretation, the cat's wave function exists in two superimposed states—dead cat/live cat. In other words, it is simultaneously dead and alive—a view that Einstein and Schrödinger regarded as absurd.

Einstein did not deny the ability of quantum mechanics to predict experimental results, but he strongly felt that it remained a partial explanation that would be eventually subsumed in a more encompassing theory. In a letter to Max Born in 1926, Einstein summed up his stance: "Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing. The theory says a lot, but does not really bring us any closer to the secret of the 'old one' [God]. I, at any rate, am convinced that *He* is not playing at dice." [21]

Einstein's objections stemmed from a deeply-held conviction that matter exists independently of the observer, is law-governed and knowable. His references to "God" did not mark a reversion to religion, but expressed a certain awe at the workings of nature. As he explained on several occasions, he used the term in the same manner as that extraordinary philosopher of the early Enlightenment—Benedict Spinoza. For Spinoza, an atheist in all but name, "God" and "nature" were interchangeable—God's laws were the laws of nature and there was no room for divine intervention. It was inconceivable to Einstein that the laws of nature, at any level, were the result of the operation of blind chance, which was not susceptible to deeper explanation.

Who was right? The unstated verdict among many was that Bohr emerged victorious. The proof of the pudding was in the eating, so to speak: on the practical level quantum mechanics worked. Several generations of physicists were taught how to use Schrödinger's wave equation to solve many and varied problems without asking too many questions about what it meant. Until more recently, the Bohr-Einstein debate was largely forgotten. After his great breakthroughs in relativity theory, it has been said, Einstein devoted himself, unsuccessfully, to the quixotic effort of developing a unified field theory encompassing all known forces.

Any notion that, after 1915, or after the debate with Bohr, Einstein became something of a scientific has-been, would be very short-sighted. Quite apart from the continuing flow of scientific papers on many topics, Einstein's objections to quantum mechanics were not a reflection of inherent conservatism, but rather of his striving for a more profound explanation of the universe. Bohr, certainly, regarded Einstein as a formidable intellectual opponent who compelled him to refine his own ideas. And Einstein remained deeply engaged in the ongoing discussions over quantum mechanics until his death in 1955.

Abraham Pais, one of Einstein's colleagues and biographers, observed: "It became clear to me from listening to them both [Einstein and Bohr] that the advent of quantum mechanics in 1925 represented a far greater break with the past than had been the case with the coming of special relativity in 1905 or of general relativity in 1915. That had not been obvious to me earlier, as I belong to a generation which was exposed to 'ready-made' quantum mechanics. I came to understand how wrong I was in accepting a rather widespread belief that Einstein did not care anymore about the quantum mechanics. On the contrary, he wanted nothing more than to find a unified field theory which not only would join together gravitational and electromagnetic forces but also would provide the basis for a new interpretation of quantum phenomena. About relativity he spoke with detachment, about the quantum theory with passion. The quantum was his demon." [22]

Schrödinger's cat has been the subject of protracted debate. The Copenhagen interpretation is not the only framework for quantum mechanics and decades of effort have refined the discussion. Nevertheless, Einstein's concerns about the interpretation of quantum mechanics remain. Moreover, even where Einstein has been shown to be wrong, his "errors" have proven to be remarkably fertile. One example was a paper that Einstein wrote jointly with Boris Pololsky and Nathan Rosen in 1935. Commonly referred to as the EPR paper, it contained one of Einstein's "thought experiments" aimed at demonstrating that the Copenhagen interpretation could not hold in all situations.

According to the Heisenberg uncertainty principle, it was impossible to simultaneously measure position and momentum beyond a certain accuracy. What if, Einstein reasoned, two subatomic particles interacted and flew apart in opposite directions. One could measure their momentum at the time of interaction, then, some time later, the position of particle A and the momentum of particle B. The information could then be used to calculate the momentum and position of both particles to any degree of accuracy. The only way to save the uncertainty principle was if making a measurement on particle A instantaneously affected particle B, and vice versa. Einstein dismissed this possibility as "spooky action at a distance".

According to one account, the EPR paper hit Bohr like "a bolt from the blue" and he spent six weeks developing a retort to the challenge. The discussion was largely forgotten until 1966, when physicist John Bell, who shared Einstein's concerns about quantum mechanics, devised a way of putting the EPR “thought experiment” to a practical test. It was not until the 1980s that the technical means became available to conclusively carry out a version of Bell’s proposal. An experimental team headed by Alain Aspect, studying the behaviour of pairs of photons, verified the predictions of quantum mechanics. Spooky action at a distance, more commonly known as quantum entanglement, is now a subject of intense study.

Quantum entanglement, however, only highlights a more fundamental problem. If pairs of particles can be instantaneously influenced over any distance, then relativity theory appears to be violated: nothing can travel faster than the speed of light. This is just one indication of what is well known: the two pillars of modern physics—quantum mechanics and general relativity—are in conflict with each other at a very fundamental level. Decades of attempts to combine the two theories have produced only partial successes.

In the opening of his book “the Elegant Universe,” Brian Greene summed up the problem: “Through years of research, physicists have experimentally confirmed to almost unimaginable accuracy all predictions made by each of these theories. But these same theoretical tools inexorably lead to another disturbing conclusion: As they are currently formulated, general relativity and quantum mechanics *cannot both be right.* The two theories underlying the progress of physics during the last hundred years—progress that has explained the expansion of the heavens and the fundamental structure of matter—are mutually incompatible.” [23]

Einstein’s preoccupation with a unified field theory stemmed from his awareness of this contradiction. In many ways, the state of physics in the early twenty-first century bears an uncanny resemblance to the situation prior to 1905. Two theories—general relativity and quantum mechanics—each extraordinarily successful within their own sphere, raise fundamental theoretical difficulties when attempts are made to unify them. The task is becoming all the more pressing as experimental data plumb the atom more deeply, and new astronomical observations pose challenges to the development of a comprehensive theory of the universe. The new problems call for more than the previous ad hoc attempts to blend the two theories. A new synthesis is needed.

Is that possible? Greene’s book is devoted to a popular exposition of superstring theory, currently the most likely contender for what is loosely referred to as TOE (a theory of everything). A sign of the times is another notable parallel. The reaction to the current ferment in physics has produced a range of opinion similar to that in 1905: from those who declare a new synthesis is impossible and, in some cases, turn to religion for answers, to others ready to proclaim a major crisis in science. There is even one author who declares that nothing much remains to be done [24]. In the final analysis, there is no doubt that Einstein’s basic intuition will eventually be proven correct: objective reality is law-governed and it is possible to penetrate ever-deeper into those laws.

A significant difference, however, between 1905 and 2005 is the general ideological atmosphere conditioned by the underlying social decay of capitalism. Whereas in 1905 there was a climate of optimism and enthusiastic interest in scientific achievements, science today is forced to defend its most basic precepts in the face of superstition, mysticism and anti-scientific nonsense, all of which are promoted for politically reactionary ends. The media coverage afforded to the Pope’s recent death, and the various mediaeval rituals associated with it, will far outweigh, for example, any examination of the contribution of Einstein over the past 100 years. That is all the more reason for socialists, and anyone preoccupied with mankind’s future progress, to pay tribute to his astonishing achievements and to defend those who continue his legacy: extending the boundaries of our knowledge of nature and the universe.

Concluded

Notes:

18. Quoted in *Einstein 1905 The Standard of Greatness*, John S. Rigden, Harvard University Press, 2005, p.36

19. Quoted in *Science: A History*, John Gribbin, Penguin, 2003, p.520

20. *The Elegant Universe*, Brian Greene, Vintage, 2000, p.106

21. Quoted in *Einstein: A Life in Science*, Michael White and John Gribbin, Simon & Schuster, 2005, p. 216

22. *Subtle is the Lord: The Science and the Life of Albert Einstein*, Abraham Pais, Oxford University Press 1982, p.9

23. Greene, op cit. p.9

24. Detailed in “A Postmodernist attack on science”, Chris Talbot, *World Socialist Web Site*, 18 May 1999