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OP-ED CONTRIBUTOR

One Hundred Years of Uncertainty

By BRIAN GREENE

JUST about a hundred years ago, Albert Einstein began writing a paper that secured his place in the pantheon of humankind's greatest thinkers. With his discovery of special relativity, Einstein upended the familiar, thousands-year-old conception of space and time. To be sure, even a century later, not everyone has fully embraced Einstein's discovery. Nevertheless, say "Einstein" and most everyone thinks "relativity."

What is less widely appreciated, however, is that physicists call 1905 Einstein's "miracle year" not because of the discovery of relativity alone, but because in that year Einstein achieved the unimaginable, writing four papers that each resulted in deep and formative changes to our understanding of the universe. One of these papers - not on relativity - garnered him the 1921 Nobel Prize in physics. It also began a transformation in physics that Einstein found so disquieting that he spent the last 30 years of his life in a determined effort to repudiate it.

Two of the four 1905 papers were indeed on relativity. The first, completed in June, laid out the foundations of his new view of space and time, showing that distances and durations are not absolute, as everyone since Newton had thought, but instead are affected by one's motion. Clocks moving relative to one another tick off time at different rates; yardsticks moving relative to one another measure different lengths. You don't perceive this because the speeds of everyday life are too slow for the effects to be noticeable. If you could move near the speed of light, the effects would be obvious.

The second relativity paper, completed in September, is a three-page addendum to the first, which derived his most famous result, E = mc2, an equation as short as it is powerful. It told the world that matter can be converted into energy - and a lot of it - since the speed of light squared (c2) is a huge number. We've witnessed this equation's consequences in the devastating might of nuclear weapons and the tantalizing promise of nuclear energy.

The third paper, completed in May, conclusively established the existence of atoms - an idea discussed in various forms for millenniums - by showing that the numerous microscopic collisions they'd generate would account for the observed, though previously unexplained, jittery motion of impurities suspended in liquids.

With these three papers, our view of space, time and matter was permanently changed.

Yet, it is the remaining 1905 paper, written in March, whose legacy is arguably the most profound. In this work, Einstein went against the grain of conventional wisdom and argued that light, at its most elementary level, is not a wave, as everyone had thought, but actually a stream of tiny packets or bundles of energy that have since come to be known as photons.

This might sound like a largely technical advance, updating one description of light to another. But through subsequent research that amplified and extended Einstein's argument (see Figures 1 through 3), scientists revealed a mathematically precise and thoroughly startling picture of reality called quantum mechanics.

Before the discovery of quantum mechanics, the framework of physics was this: If you tell me how things are now, I can then use the laws of physics to calculate, and hence predict, how things will be later. You tell me the velocity of a baseball as it leaves Derek Jeter's bat, and I can use the laws of physics to calculate where it will land a handful of seconds later. You tell me the height of a building from which a flowerpot has fallen, and I can use the laws of physics to calculate the speed of impact when it hits the ground. You tell me the positions of the Earth and the Moon, and I can use the laws of physics to calculate the date of the first solar eclipse in the 25th century. What's important is that in these and all other examples, the accuracy of my predictions depends solely on the accuracy of the information you give me. Even laws that differ substantially in detail - from the classical laws of Newton to the relativistic laws of Einstein - fit squarely within this framework.

Quantum mechanics does not merely challenge the previous laws of physics. Quantum mechanics challenges this centuries-old framework of physics itself. According to quantum mechanics, physics cannot make definite predictions. Instead, even if you give me the most precise description possible of how things are now, we learn from quantum mechanics that the most physics can do is predict the probability that things will turn out one way, or another, or another way still.

The reason we have for so long been unaware that the universe evolves probabilistically is that for the relatively large, everyday objects we typically encounter - baseballs, flowerpots, the Moon - quantum mechanics shows that the probabilities become highly skewed, hugely favoring one outcome and effectively suppressing all others. A typical quantum calculation reveals that if you tell me the velocity of something as large as a baseball, there is more than a 99.99999999999999 (or so) percent likelihood that it will land at the location I can figure out using the laws of Newton or, for even better accuracy, the laws of Einstein. With such a skewed probability, the quantum reasoning goes, we have long overlooked the tiny chance that the baseball can (and, on extraordinarily rare occasions, will) land somewhere completely different.

When it comes to small objects like molecules, atoms and subatomic particles, though, the quantum probabilities are typically not skewed. For the motion of an electron zipping around the nucleus of an atom, for example, a quantum calculation lays out odds that are all roughly comparable that the electron will be in a variety of different locations - a 13 percent chance, say, that the electron will be here, a 19 percent chance that it will be there, an 11 percent chance that it will be in a third place, and so on. Crucially, these predictions can be tested. Take an enormous sample of identically prepared atoms, measure the electron's position in each, and tally up the number of times you find the electron at one location or another. According to the pre-quantum framework, identical starting conditions should yield identical outcomes; we should find the electron to be at the same place in each measurement. But if quantum mechanics is right, in 13 percent of our measurements we should find the electron here, in 19 percent we should find it there, in 11 percent we should find it in that third place. And, to fantastic precision, we do.

Faced with a mountain of supporting data, Einstein couldn't argue with the success of quantum mechanics. But to him, even though his own Nobel Prize-winning work was a catalyst for the quantum revolution, the theory was anathema. Commentators over the decades have focused on Einstein's refusal to accept the probabilistic framework of quantum mechanics, a position summarized in his frequent comment that "God does not play dice with the universe." Einstein, radical thinker that he was, still believed in the sanctity of a universe that evolved in a fully definite, fully predictable manner. If, as quantum mechanics asserted, the best you can ever do is predict probabilities, Einstein countered that he'd "rather be a cobbler, or even an employee in a gaming house, than a physicist."

This emphasis, however, partly obscures a larger point. It wasn't the mere reliance on probabilistic predictions that so troubled Einstein. Unlike many of his colleagues, Einstein believed that a fundamental physical theory was much more than the sum total of its predictions - it was a mathematical reflection of an underlying reality. And the reality entailed by quantum mechanics was a reality Einstein couldn't accept.

An example: Imagine you shoot an electron from here and a few seconds later it's detected by your equipment over there. What path did the electron follow during the passage from you to the detector? The answer according to quantum mechanics? There is no answer. The very idea that an electron, or a photon, or any other particle, travels along a single, definite trajectory from here to there is a quaint version of reality that quantum mechanics declares outmoded.

Instead, the proponents of quantum theory claimed, reality consists of a haze of all possibilities - all trajectories - mutually commingling and simultaneously unfolding. And why don't we see this? According to the quantum doctrine, when we make a measurement or perform an observation, we force the myriad possibilities to ante up, snap out of the haze and settle on a single outcome. But between observations - when we are not looking - reality consists entirely of jostling possibilities.

Quantum reality, in other words, remains ambiguous until measured. The reality of common perception is thus merely a definitive-looking veneer obscuring the internal workings of a highly uncertain cosmos. Which is where Einstein drew a line in the sand. A universe of this sort offended him; he could not accept, as he put it, that "the Old One" would so profoundly incorporate a hidden element of happenstance in the nature of reality. Einstein quipped to his quantum colleagues, "Do you really think the Moon is not there when you're not looking?" and set himself the Herculean task of reworking the laws of physics to resurrect conventional reality.

Einstein waged a two-front assault on the problem. He sought an internal chink in the quantum framework that would establish it as a mere steppingstone on the path to a deeper and more complete description of the universe. At the same time, he sought a grander synthesis of nature's laws - what he called a "unified theory" - that he believed would reveal the probabilities of quantum mechanics to be no more profound than the probabilities offered in weather forecasts, probabilities that simply reflect an incomplete knowledge of an underlying, definite reality.

In 1935, through a disarmingly simple mathematical analysis, Einstein (with two colleagues) established a beachhead on the first front. He proved that quantum mechanics is either an incomplete theory or, if it is complete, the universe is - in Einstein's words - "spooky." Why "spooky?" Because the theory would allow certain widely separated particles to correlate their behaviors perfectly (somewhat as if a pair of widely separated dice would always come up the same number when tossed at distant casinos). Since such "spooky" behavior would border on nuttiness, Einstein thought he'd made clear that quantum theory couldn't yet be considered a complete description of reality.

The nimble quantum proponents, however, would have nothing of it. They insisted that quantum theory made predictions - albeit statistical predictions - that were consistently born out by experiment. By the precepts of the scientific method, they argued, the theory was established. They maintained that searching beyond the theory's predictions for a glimpse of a reality behind the quantum equations betrayed a foolhardy intellectual greediness.

Nevertheless, for the remaining decades of his life, Einstein could not give up the quest, exclaiming at one point, "I have thought a hundred times more about quantum problems than I have about relativity." He turned exclusively to his second line of attack and became absorbed with the prospect of finding the unified theory, a preoccupation that resulted in his losing touch with mainstream physics. By the 1940's, the once dapper young iconoclast had grown into a wizened old man of science who was widely viewed as a revolutionary thinker of a bygone era.

By the early 1950's, Einstein realized he was losing the battle. But the memories of his earlier success with relativity - "the years of anxious searching in the dark, with their intense longing, their alternations of confidence and exhaustion and the final emergence into the light" - urged him onward. Maybe the intense light of discovery that had so brilliantly illuminated his path as a young man would shine once again. While lying in a bed in Princeton Hospital in mid-April 1955, Einstein asked for the pad of paper on which he had been scribbling equations in the desperate hope that in his final hours the truth would come to him. It didn't.

Was Einstein misguided? Must we accept that there is a fuzzy, probabilistic quantum arena lying just beneath the definitive experiences of everyday reality? As of today, we still don't have a final answer. Fifty years after Einstein's death, however, the scales have certainly tipped farther in this direction.

Decades of painstaking experimentation have confirmed quantum theory's predictions beyond the slightest doubt. Moreover, in a shocking scientific twist, some of the more recent of these experiments have shown that Einstein's "spooky" processes do in fact take place (particles many miles apart have been shown capable of correlating their behavior). It's a stunning finding, and one that reaffirms Einstein's uncanny ability to unearth features of nature so mind-boggling that even he couldn't accept what he'd found. Finally, there has been tremendous progress over the last 20 years toward a unified theory with the discovery and development of superstring theory. So far, though, superstring theory embraces quantum theory without change, and has thus not revealed the definitive reality Einstein so passionately sought.

With the passage of time and quantum mechanics' unassailable successes, debate about the theory's meaning has quieted. The majority of physicists have simply stopped worrying about quantum mechanics' meaning, even as they employ its mathematics to make the most precise predictions in the history of science. Others prefer reformulations of quantum mechanics that claim to restore some features of conventional reality at the expense of additional - and, some have argued, more troubling - deviations (like the notion that there are parallel universes). Yet others investigate hypothesized modifications to the theory's equations that don't spoil its successful predictions but try to bring it closer to common experience.

Over the 25 years since I first learned quantum mechanics, I've at various times subscribed to each of these perspectives. My shifting attitude, however, reflects that I'm still unsettled. Were Einstein to interrogate me today about quantum reality, I'd have to admit that deep inside I harbor many of the doubts that gnawed at him for decades. Can it really be that the solid world of experience and perception, in which a single, definite reality appears to unfold with dependable certainty, rests on the shifting sands of quantum probabilities?

Well, yes. Probably. The evidence is compelling and tangible. Although we have yet to fully lay bare quantum mechanics' grand lesson for the underlying nature of the universe, I like to think even Einstein would be impressed that in the 50 years since his death our facility with quantum mechanics has matured from a mathematical understanding of the subatomic realm to precision control. Today's technological wizardry (computers, M.R.I.'s, smart bombs) exists only because research in applied quantum physics has resulted in techniques for manipulating the motion of electrons - probabilities and all - through mazes of ultramicroscopic circuitry. Advances hovering on the horizon, like nanoscience and quantum computers, offer the promise of even more spectacular transformations.

So the next time you use your cellphone or laptop, pause for a moment. Recognize that even these commonplace devices rely on our greatest, yet most puzzling, scientific achievement and - as things now stand - tap into humankind's most supreme assault on the idea that reality is what we think it is.

Brian Greene, a professor of physics and mathematics at Columbia, is the author of "The Elegant Universe,'' and, most recently, "The Fabric of the Cosmos."

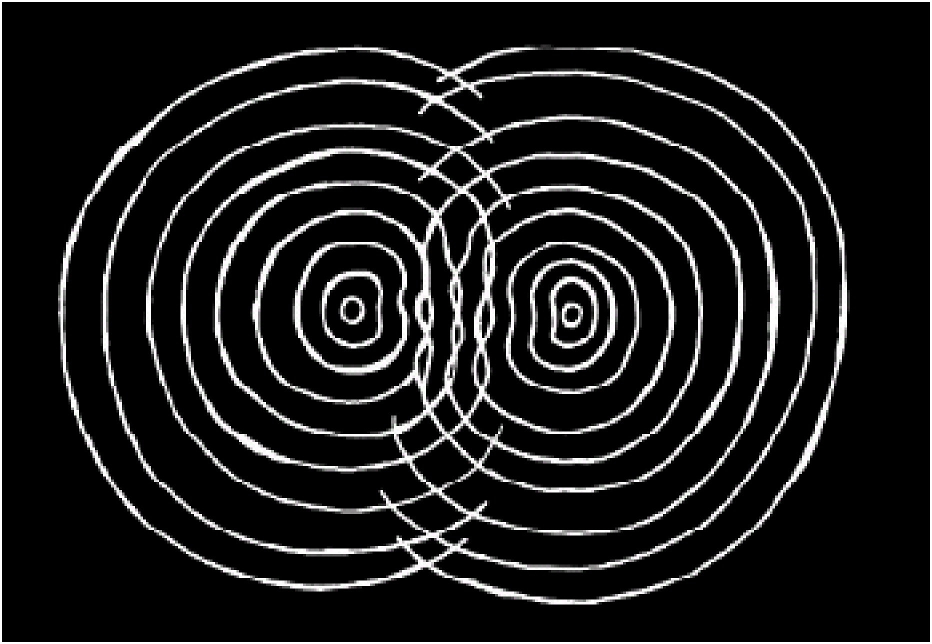

Figure 1a

The hallmark feature of waves, like those in water, is their ability to produce an interference pattern when they overlap.

Figure 1b

In the 19th century, light beams emanating from two locations — in this case, two slits — were shown to produce an interference pattern, establishing that light is a wave.

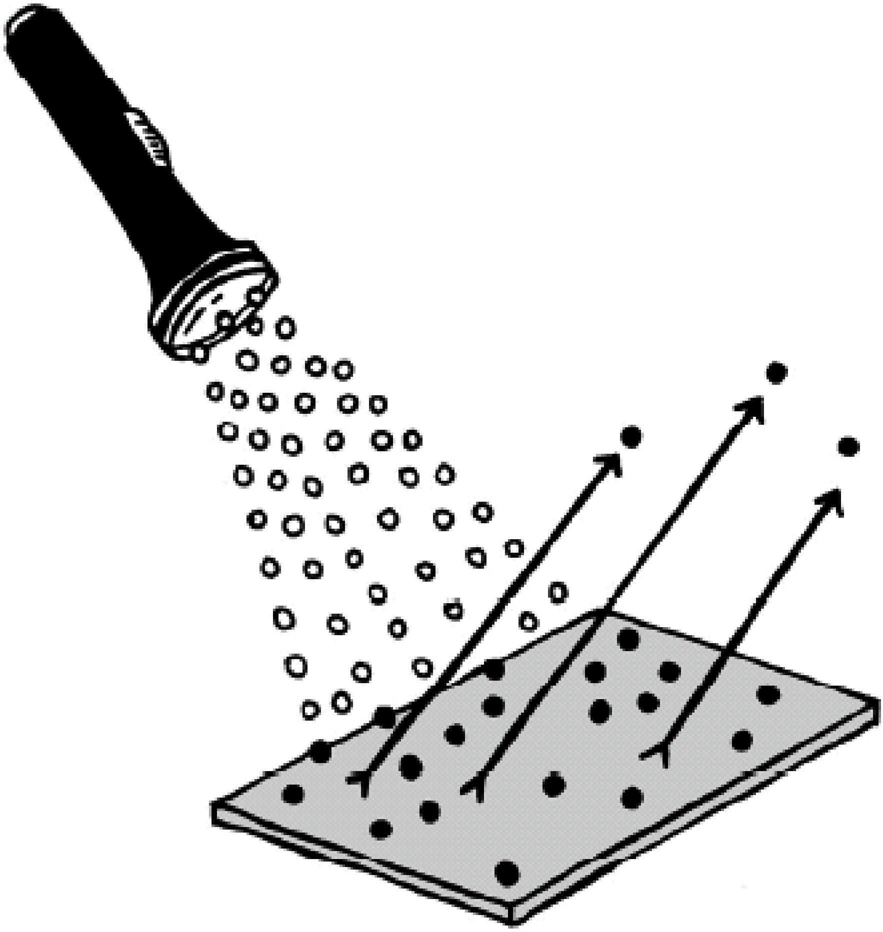

Figure 2

In 1905, Einstein challenged the wave theory of light when he showed that the photoelectric effect — the ejection of electrons from a metallic surface on which light is shone — could be explained only if light is a stream of particles, later named photons. Electrons, Einstein argued and the data resoundingly supported, are ejected when they suffer a direct hit from an incoming photon.

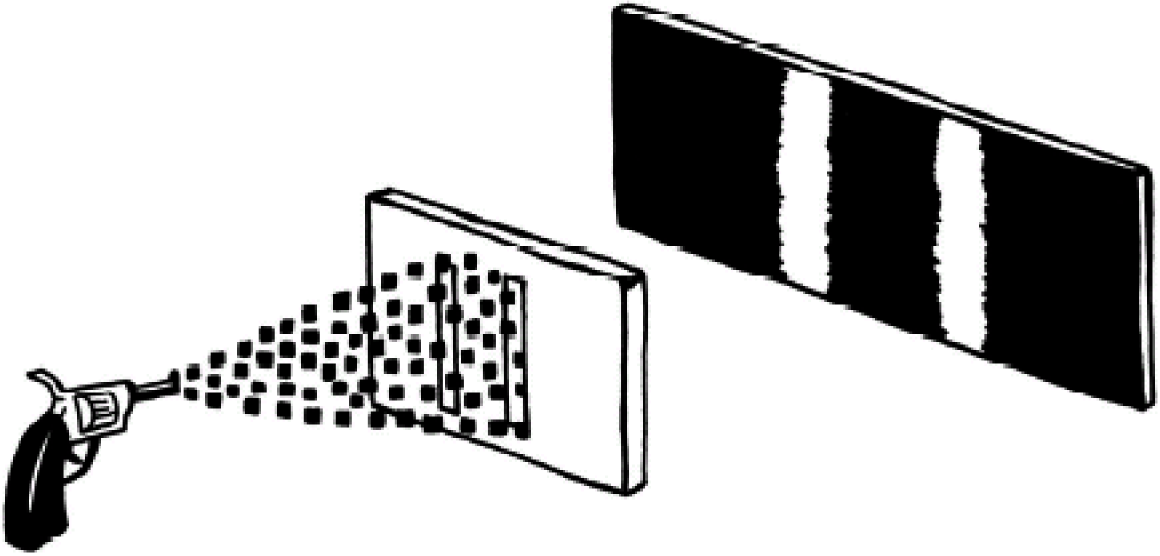

Figure 3a

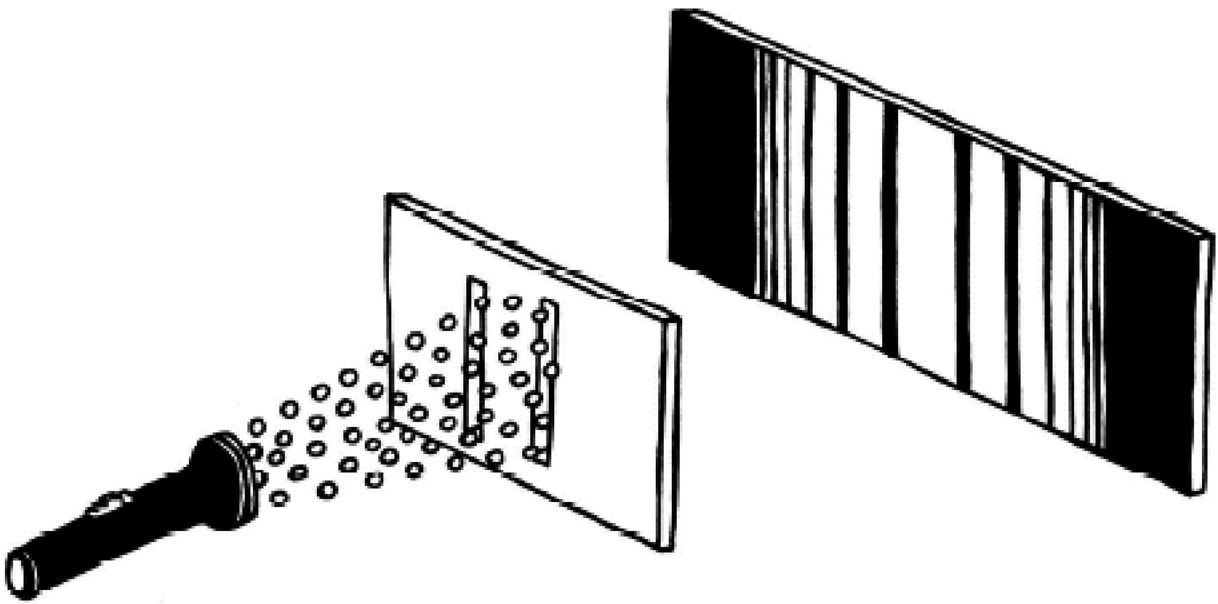

Figure 3b

(a) Particles, like bullets, fired through two slits hit a detector screen in two bands. (b) In one of the greatest scientific surprises of the 20th century, photons fired through two slits produce a wave-like interference pattern on impact — even though they are particles. This helped to establish "wave-particle" duality: everything exhibits the characteristics of both particles and waves. In seeking to understand the wave nature of particles, physicists realized that the waves were more accurately waves of probability — all they could do was give the likelihood that a particle will be found in one location or another. The probabilistic framework of quantum mechanics was born.