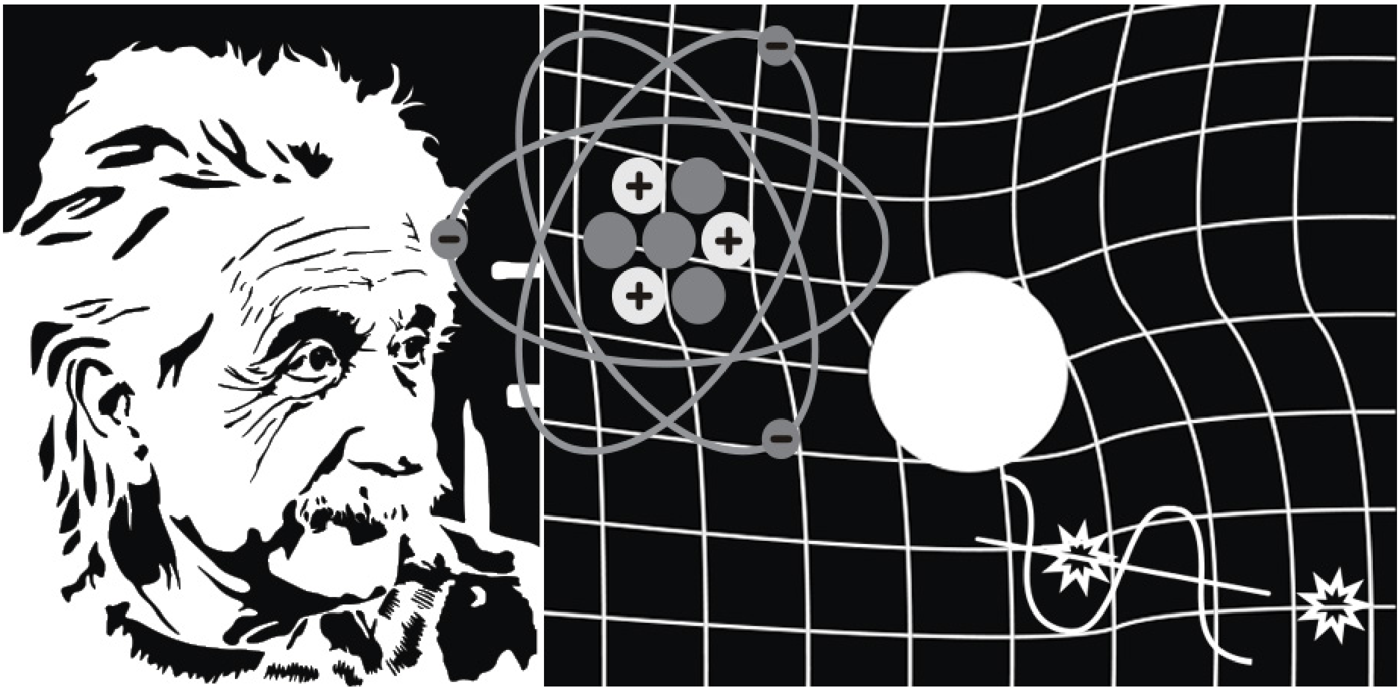
What, exactly, is a photon?

With new experiments and technologies, physicists have shown they can control individual photons with unprecedented precision. But the enigmatic elementary particle still hides its true colors.

01 November 2020 By Sophia Chen



The photon might be the most familiar of elementary particles. Traveling at the speed of light, the particles bombard us daily from the sun, moon, and stars. For more than a century, scientists and engineers have harnessed them in aggregate to illuminate our cities and now, our screens.

Researchers today can control photons with more finesse than ever before. At the National Institute of Standards and Technology (NIST) in Maryland, physicist Paulina Kuo creates and manipulates photons individually. By illuminating custom-designed crystals with laser light in her lab, Kuo produces twin photons, which she can further separate into single photons. Directing them toward certain materials, which absorb the particle to produce photons of different colors, she can effectively change the color of a photon while preserving the information encoded in it.

For example, she designed a crystal to double the frequency of an input photon, enabling conversion between red and infrared light. "You can fuse two photons together, or split one photon into two," she says. "Or even higher order processes. You can fuse three photons into one, or split one photon into three." Complementing these techniques, she uses state-of-the-art single-photon detectors, made of superconducting wires that become nonsuperconducting when they absorb a single photon. These types of detectors deliver highly accurate counts, detecting photons with up to 99 percent efficiency.

This single-photon technology will form the backbone of a future quantum internet, a proposed global network of devices for transmitting data encoded in single photons and other quantum particles. This data would be represented in a particle's quantum properties, such as a photon's polarization. Unlike classical data, which can only be represented as 0 or 1, so-called quantum information takes on values that are weighted combinations of 0 and 1, which enables new, potentially more powerful computational algorithms and new encryption protocols.

Engineering challenges abound for the quantum internet, such as problems with signal loss, says Kuo. But researchers—and their governments—have laid ambitious plans. In 2016, the European Union began a 1-billion euro quantum technologies initiative. This August, the US established five quantum research centers for accelerating quantum technology development with up to $625 million promised over the next five years. Physicist Pan Jian-Wei, who spearheaded the 2016 launch of a $100 million Chinese quantum technology satellite and its subsequent projects, has described a goal of building a global quantum internet by 2030.

Many experts have dubbed the current era of single-photon technology as the "second quantum revolution," a paradigm shift where scientists not only understand the counterintuitive principles of quantum mechanics—entanglement, superposition, and wave-particle duality—but can exploit them in technologies. The photon is no longer merely an object of study, but a tool.

So what, then, is a photon? Kuo gives a circular response. "A photon is the click registered by a single-photon resolving detector," she says.

Vaguer words than Kuo's have been used to describe the photon. It's a wave and a particle of light, or it's a quantization of the electromagnetic field. Or, "Shut up and calculate," a phrase familiar to anyone who has puzzled over quantum mechanics.

"You can get into trouble if you give the photon too much reality," says physicist Alan Migdall of NIST.

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"People have been arguing about it for 100 plus years," says physicist Aephraim Steinberg of the University of Toronto. "I don't think we've come to a consensus."

Physicists began arguing about the photon as soon as they discovered it. The very scientists who conceived of the particles were skeptical that they fundamentally existed in nature. To explain otherwise confounding experimental data regarding the relationship of an object's temperature to its emitted radiation, in 1900 the German physicist Max Planck proposed that radiation comes in discrete quantities, or quanta. The concept of the photon was born. But Planck didn't comprehend the profundity of his idea. He later described his breakthrough as "an act of desperation"—an unsubstantiated trick to make the math work out.

Albert Einstein, too, resisted implications of the photon theory that he helped to develop. He was particularly bothered by entanglement, the idea that two particles can have intertwined fates, even when they are separated far apart from each other. The theory implied, for example, that if you measured the polarization of one photon in an entangled pair, you would instantly also know the polarization of the other, even if the two particles have been separated to opposite ends of the solar system. Entanglement suggested that objects can influence each other from arbitrarily far away, known as nonlocality, which Einstein derided as "spooky action at a distance." Preferring a reality where objects must be in proximity to exert influence on each other, he believed that quantum mechanics theory was incomplete. "It certainly gave Einstein indigestion," says Migdall.

For decades, arguments over the photon were largely relegated to the realm of thought experiments, as it was technologically impossible to test these ideas. Recently, the debate has trickled into the physics community more broadly, as single-photon sources and detectors become better and more widely accessible, according to Steinberg. "We can do these experiments instead of just imagining them, like Schrödinger's cat," he says.

For example, physicists have all but confirmed the existence of entanglement. Decades of experiments, known as tests of Bell's inequality, now strongly indicate that Einstein was wrong—and that our universe is nonlocal.

These tests are based on an experimental framework devised by the UK physicist John Stewart Bell in 1964. In theoretical work, Bell showed that if you repeat measurements on purportedly entangled particles, the statistics could reveal whether the photons truly influence each other nonlocally, or if an unknown mechanism—known generically as a "local hidden variable"—creates the illusion of action at a distance. In practice, the tests have largely involved splitting up pairs of entangled photons along two different paths to measure their polarizations at two different detectors.

Physicists have been performing Bell tests since the 1970s, with all published experiments indicating photons can spookily act from a distance, as physicist David Kaiser of the Massachusetts Institute of Technology explains. However, despite unanimous results, these early experiments were inconclusive: Technology shortfalls meant their experiments suffered from three potential design limitations, or loopholes.

The first loophole, known as the locality loophole, arises from the two polarization detectors being too close together. Theoretically, it was possible that one detector could have relayed a signal to the other detector right before the entangled photons are emitted, influencing the outcome of the measurement locally.

The second loophole, called the fair sampling loophole, resulted from poor-quality single-photon detectors. Experts argued that the detectors could have caught a biased subset of the photons, skewing the statistics. The desire to close this loophole, says Migdall, has driven the development of better single-photon detectors, the same now used routinely in quantum technologies.

The third loophole, the freedom-of-choice loophole, is related to the settings of the polarization detector. To get truly unbiased statistics on a large number of polarization measurements, the orientation of the polarization detector must be randomly reset for each measurement. It is difficult to guarantee randomness, with researchers painstakingly resetting the detectors by hand in early experiments.

Recent experiments have closed all three loopholes, albeit not simultaneously in one test, according to Kaiser. In 2015, a team led by physicist Ronald Hanson at the Delft University of Technology performed a Bell test that closed the fair sampling and locality loopholes for the first time, albeit using entangled electrons rather than photons.

Publishing in 2018, a team of scientists at the Institute of Photonics Sciences in Spain charged 100,000 volunteers to play a video game to generate random numbers, which the scientists used to set their Bell test detectors to constrain the freedom-of-choice loophole.

Kaiser worked on another experiment published in 2018, dubbed the "Cosmic Bell Test," which closed the locality loophole and tightly constrained the freedom-of-choice loophole by setting their polarization detector orientation using a random number generator based on the frequency of light emitted from two stars 600 and 1,900 light years away, respectively.

The results strongly support the nonlocality of entanglement. "The indigestion that Einstein had with quantum mechanics—if he were around today, you would tell him that he would just have to deal with it," says Migdall.

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Physicist Alexandra Landsman of The Ohio State University describes the photon as "a quantum of energy," which aligns closely with physicists' original conceptions of the particle. In a 1905 paper, Einstein described light as discrete packets of energy proportional to its frequency to explain the so-called photoelectric effect. Scientists had observed that materials absorb light to eject electrons, but only when the frequency of the light is shorter than some threshold value. Einstein's explanation, for which he was awarded the Nobel Prize in 1921, helped to kickstart the development of quantum theory.

New laser technology has enabled researchers to revisit the photoelectric effect in more detail. Attosecond lasers, invented in 2001, deliver pulses of light less than a quadrillionth of a second long that allow physicists to observe quantum-scale action like a camera with record shutter speed. In particular, physicists are using ultrafast lasers to time the photoelectric effect: once a photon impinges upon an atom or molecule, how long does it take the electron to be ejected? "People in the past assumed that this process happens instantaneously," says Landsman. "There was no way to address this question experimentally."

In 2010, a team led by physicist Ferenc Krausz, then at Vienna University of Technology, performed an experiment showing that electron ejection from an atom takes time. While they didn't measure the absolute time, they could discern that it took about 20 attoseconds longer for an electron to leave from the 2p orbital versus the 2s orbital of a neon atom. Subsequent experiments by other groups have timed the electron emission in molecules such as water and nitrous oxide.

Landsman, a theorist, is working to understand why electrons leave certain molecules faster than others. Some molecules, for example, confine the electron to a space such that the electron forms a standing wave. This condition, known as shape resonance, temporarily traps the electron, slowing down its escape. Ultimately, Landsman wants to elucidate all the factors that delay atoms and molecules from releasing the electron to zero in on how long the photon and electron encounter each other. "These experiments give us more insight as to how a photon interacts with an electron," she says.

Zlatko Minev, however, does not think that a photon is a quantum of energy. Minev, a physicist at IBM, researches how to build a quantum computer. In this new technological context, he says, photons seem to manifest differently.

Minev runs experiments on circuits made of superconducting wires that can be used as qubits, which are building blocks of quantum computers. These circuits are designed to absorb a single photon of a specified energy, where the absorption of a photon can represent the 1 state in a quantum computer. Once the qubit absorbs one photon, its response changes, so that it will no longer absorb photons of that energy.

The conventional idea of a photon as a "quantum of energy" doesn't fit these circuits, says Minev, who refers to the systems as quantum nonlinear oscillators. "You could ask, what does it mean to have two photons in my oscillator? Is it two units of energy?" he says. "In this case, it's not, because each extra photon in the oscillator actually has a different amount of energy. The energy doesn't define the photon in this case."

So how does he describe the photon? "I'm not sure I can give you a one-sentence answer," says Minev. "I'm currently reevaluating my own understanding." Currently, he thinks the photon is a "quantum of action," where "action" refers to an abstract quantity describing the allowed behavior of his system.

As physicists reevaluate the basics, these new experiments illuminate the connection between fundamental science and applications. Kuo's quantum internet technology shares ancestry with the hardware used in Bell tests of entanglement. Minev's studies of his nonlinear oscillator help him develop methods to correct errors in quantum computers. Landsman's research on the photoelectric effect in molecules can reveal clues about its electronic properties, which could eventually provide scientists a new avenue for designing materials with desired specifications. Migdall says that researchers use Bell tests to verify randomness in new models of random number generators that exploit entangled particles.

Still, the true nature of the photon eludes physicists. "All the fifty years of conscious brooding have brought me no closer to the answer to the question: What are light quanta?" Einstein wrote in a 1951 letter. "Of course today every rascal thinks he knows the answer, but he is deluding himself."

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He may have been wrong about entanglement, but seven more decades of collective brooding later, the sentiment still holds.

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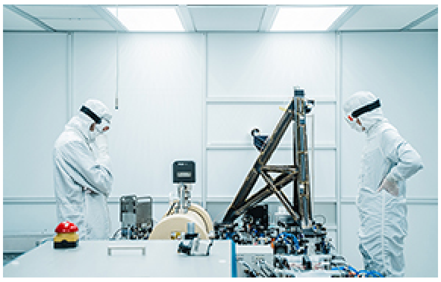

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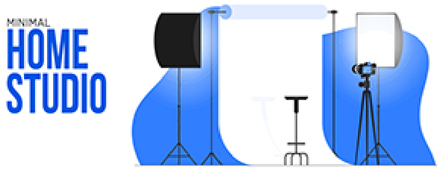

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