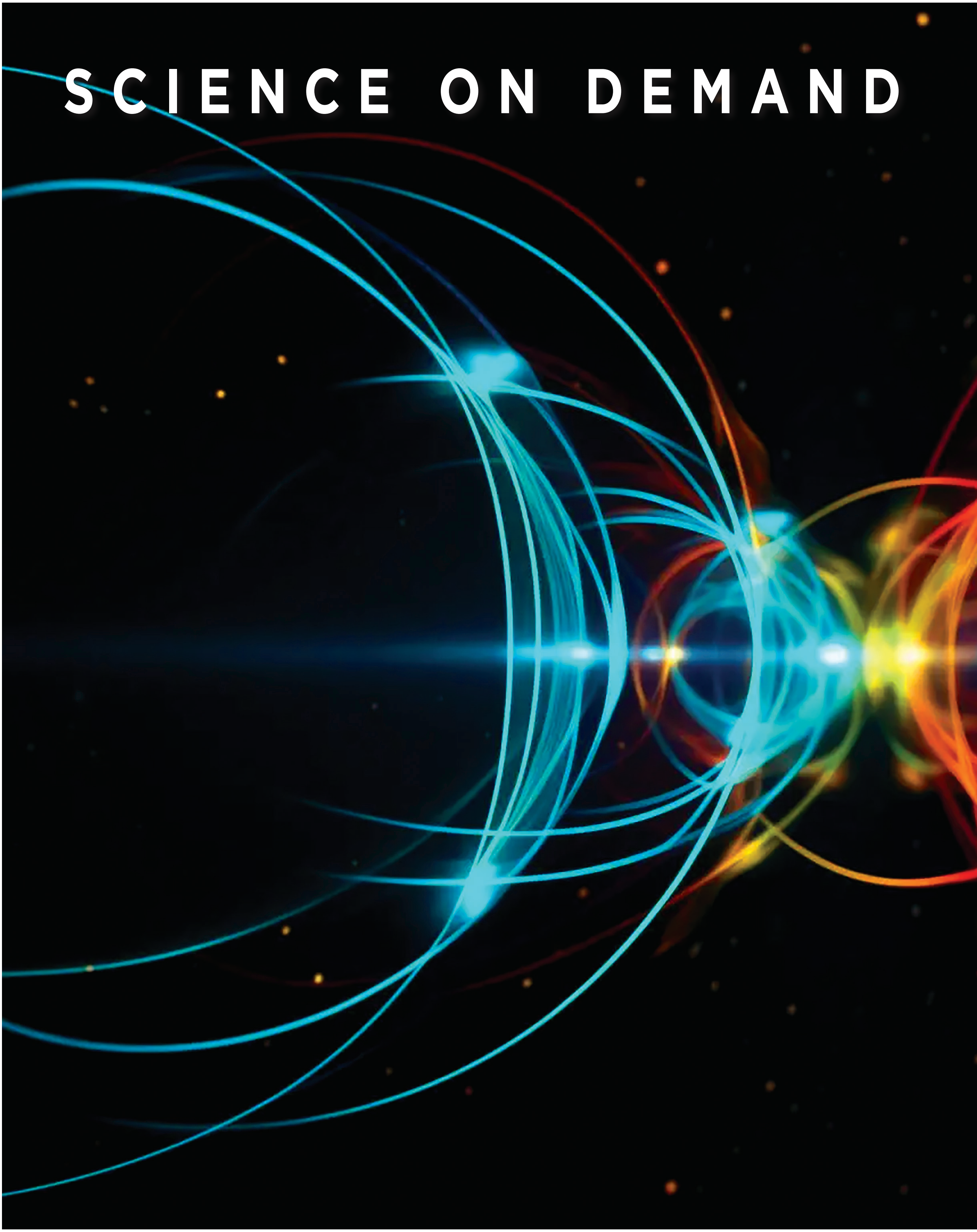
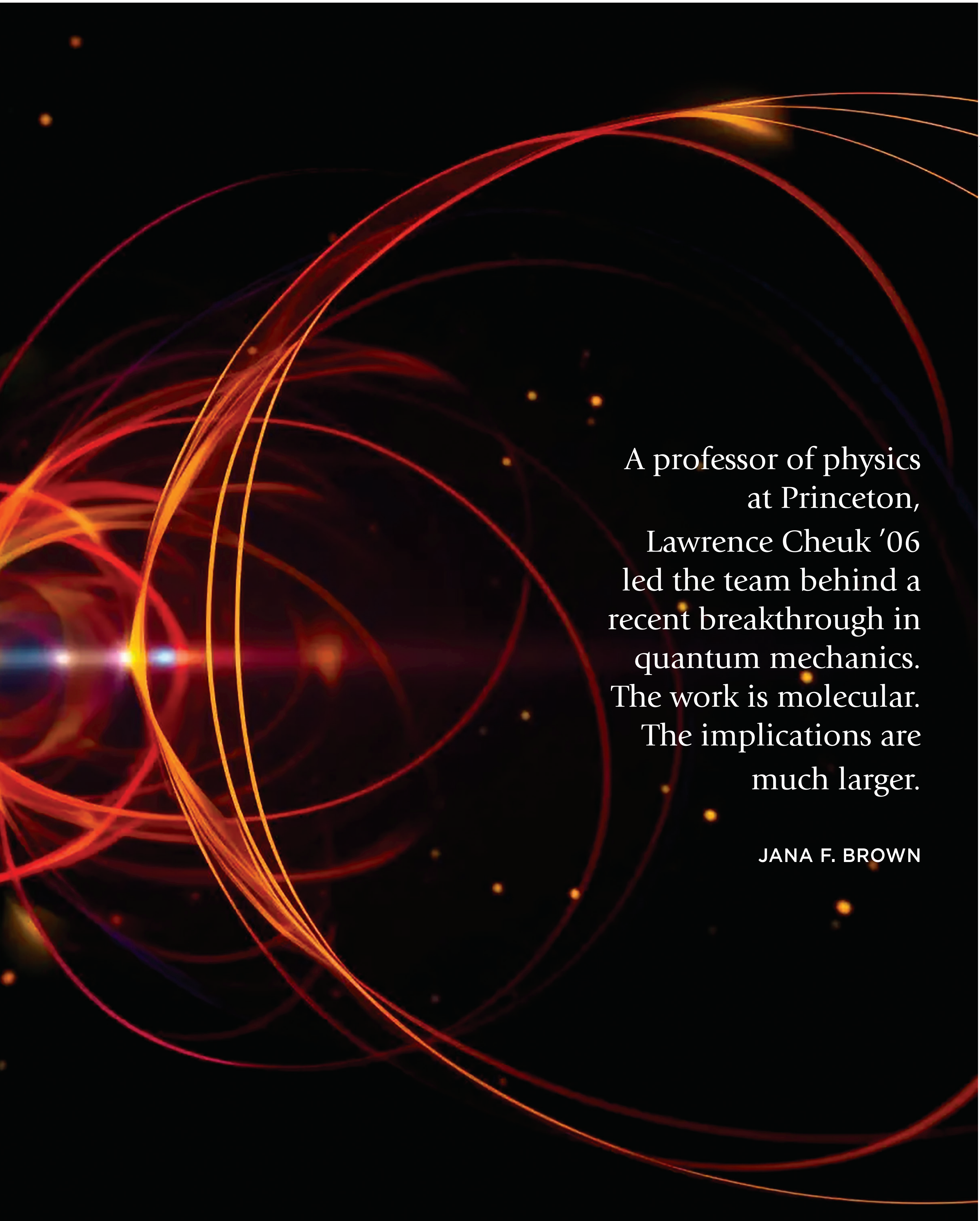
SCIENCE ON DEMAND





REVOLUTIONIZED.COM/QUANTUM-ENTANGLEMENT-EXPLAINED

A professor of physics at Princeton, Lawrence Cheuk ’06 led the team behind a recent breakthrough in quantum mechanics. The work is molecular. The implications are much larger.

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For the average student in the average physics class, "simplicity, elegance and beauty" might not be the first descriptors that come to mind when talking about the discipline. They are, however, the adjectives Lawrence Cheuk '06 uses when he explains what drew him to the field.

"Physics provides an understanding of how nature behaves," Cheuk explains. "We try to describe things using only a few simple principles, and it's remarkable to me that a lot of physics can be reduced down to a few fundamental rules. It's this special way of describing nature and predicting what should happen."

Of course, as a physicist and assistant professor of physics at Princeton University, Cheuk is about the furthest thing possible from an average physics student. Indeed, his work is anything but simple even to those working in the field of quantum mechanics, the discipline widely associated with Albert Einstein, who helped develop quantum theory only to later reject its further development with the famous observation, "God does not play dice with the Universe." In December 2023, Cheuk, along with co-authors Connor Holland and Yukai Lu, published "On-Demand Entanglement of Molecules in a Reconfigurable Optical Tweezer Array" in the peer-reviewed journal "Science." The research revealed in the paper is considered a major breakthrough in quantum science and involves demonstrating for the first time the "quantum entanglement" of molecules: a state in which two separated particles can be shown to predictably interact with each other without being in direct contact.

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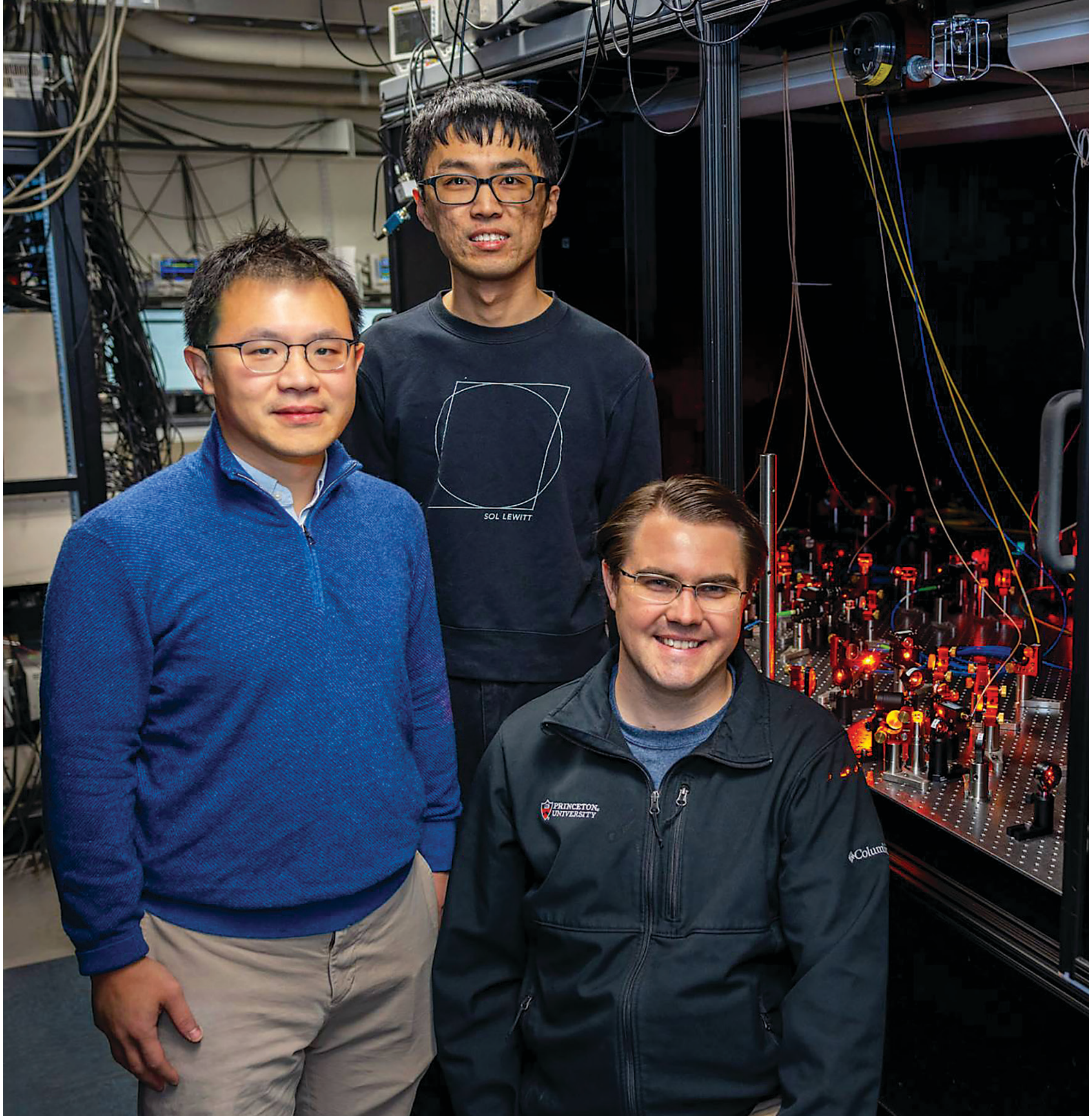
As Cheuk explains, quantum mechanics is a theory that describes nature in a way that's "all around us." On a practical level, scientists have discovered theoretically that one can use quantum mechanics to enhance real-world applications, such as secure communications and computing. And at the heart of the "quantum advantage" in these applications is entanglement. Yet entanglement is fragile and difficult to create in the lab. Over the years, scientists have tried to create and control entanglement in a variety of different physical platforms.

"They have used photons, which [are] the smallest unit of light," Cheuk says. "They have used trapped ions, which are charged atoms. They have used neutral atoms. In all these platforms, scientists have shown that they have the control capability to produce entanglement on demand."

What's novel in the work of Cheuk, Holland and Lu is that the three Princeton scientists looked at entanglement using a new platform: molecules. The significance may require a quick physics refresher to fully appreciate. Photons are subatomic particles that physicists believe are not further divisible into any other form of matter. Atoms are the smallest units of matter that define discrete elements, based on their makeup of protons, neutrons and electrons. Molecules are groups of atoms held together by chemical bonds and represent the smallest unit of a substance that retains all of the substance's defining properties (think water, nitrogen, table salt) and possess what Cheuk describes as many more internal degrees of freedom than atoms. "Molecules can rotate about themselves, and the atoms within a molecule can vibrate in many ways. These are useful in quantum applications because it allows new ways to encode quantum information, and new ways to process it, since molecules can interact in many more ways compared to photons and atoms."

It is this complexity of the way molecules interact that Cheuk and his co-authors have leveraged to make an advancement in the field. "What we did," Cheuk says, "was demonstrate that we can grab onto single molecules and position them at will, and also make them interact coherently with each other on demand. Even more importantly, we can actually — by controlling how long they interact — provably make them entangled. This is a big step forward because entanglement is the fundamental ingredient in many proposed quantum applications. It's also the crucial building block needed to explore many areas of quantum science using molecules."

Originally from Hong Kong, Cheuk arrived at St. Paul's School in the fall of 2002, alongside his brother, Eddie



Cheuk (l.) with co-authors Yukai Lee and Connor Holland. Photo: Richard Soden, Department of Physics, Princeton University.

’05. He brought with him a curiosity and penchant for science and says his interest in math and physics was developed at the School under the direction of former faculty members Larry Braden, Michelle Harth and Tom McCarthy. During Cheuk’s first year at SPS, it became evident to Harth that the Third Former was capable of much more than he was learning in his Physics First class, so she enlisted McCarthy, an Advanced Placement Physics teacher at the time, to serve as the adviser to Cheuk for an experimental project in classical mechanics.

For that research, the two studied the motion of a large spool with a string attached to it to determine the mechanics of its weight-driven oscillations. In what was then a relatively innovative approach, they used a video camera to track the motion and then Cheuk converted the results into data. The experiments were conducted in the SPS Hockey Center.

“Lawrence did all the math and plotted all the graphs,” recalls McCarthy, now a retired professor who most recently taught physics at Grand Canyon University. “And they’re not a trivial kind of graphs. … He definitely dug in to gather the math he needed. He also did a proof for me one time that used directional cosines. Most students at that level wouldn’t be familiar with that, but his mind was always solving problems that were well out of the reach of most people that age.”

By the time he graduated from SPS, Cheuk had distinguished himself as a talented all-around student and community member. That included becoming a Fifth Form Ferguson Scholar, being named the recipient of the Hargate Mathematics Prize in 2005 and the Vanderpoel Science Prize in 2006 — and coxing the boys varsity first boat for the SPS crew program. Though Cheuk had not taken the prerequisite class, McCarthy recommended him for Advanced Astronomy in his Sixth Form year. His devotion to the field and impressive self-motivation, says McCarthy, led to Cheuk collecting significant data and becoming a prolific producer of digital images. One of his shots of the Pleiades star cluster was published as the photo of the day by “Astronomy Magazine” in the fall of 2005.

As an undergraduate at Princeton, Cheuk earned his A.B. in physics and continued his athletic career as a coxswain for the men’s heavyweight rowing team. He gained


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Illustration of quantum entanglement: two particles that share spatial proximity.

his first true research experience during his sophomore summer working in an atomic physics lab and trying to discover evidence of new fundamental laws in the field. Cheuk's senior thesis, for which he received Princeton's Sigma Xi Book Award for Outstanding Undergraduate Research in Physics, focused on a device called a comagnetometer, a sensitive instrument that can be used as a gyroscope or for "searches of new fundamental forces in physics."

After Princeton, Cheuk earned his PhD in physics at MIT, focusing on advances in atomic phenomena that perhaps require a doctorate just to understand: using cold samples of atoms to "examine quantum many-body systems"; helping to develop a quantum gas microscope capable of "looking at arrays of single fermionic atoms trapped in standing waves of light." He received the Martin Deutsch Award for Excellence in Experimental Physics at MIT in 2013.

It was during a research post at Harvard (as a Harvard/Max-Planck Quantum Optics Postdoctoral Fellow) that Cheuk was part of a team that succeeded in trapping and detecting single molecules in optical "tweezers," or tightly focused laser beams. That discovery formed the technical basis for his current work at Princeton.

"I would say a unifying theme of my research," Cheuk says, "is controlling these atomic — and now molecular — systems at an unprecedented level and thereby exploring quantum physics with them."

To put Cheuk's newest work in context, McCarthy references a 1935 paper by Einstein, Boris Podolsky and Nathan Rosen titled "Can Quantum-Mechanical Description of Physical Reality be Considered Complete?" While Einstein did not call the research on particles "entanglement" at the time (that term eventually came from physicist Erwin Schrödinger), in last summer's box-office smash "Oppenheimer," the perplexing paradox is the subject of a theoretical conversation between Einstein and Robert Oppenheimer. In 2022, a team of scientists (Alain Aspect, John F. Clauser and Anton Zeilinger) was awarded the Nobel Prize in Physics for "experiments with entangled photons." What Cheuk and his fellow researchers have done, McCarthy explains, is apply the previous research to their work in a new way, because "nobody had done molecules, and molecules offer more variety of entanglement, and they're easier to push around and hold still with the optical tweezers."

When discussing their breakthrough, Connor Holland, one of Cheuk's first doctoral students and a co-author on the "Science" paper, calls the Princeton team's discovery the "tip of the iceberg" in terms of the role molecules could play in quantum mechanics.

"The fact that we were able to demonstrate on-demand entanglement lends weight toward molecules in optical tweezer arrays being a new and viable platform for quantum science," Holland explains. "Many more improvements to the system will be needed as we scale to larger system sizes and as we look to explore more subtle phenomena. But the demonstration is a metaphorical 'flag in the ground,' showing all the necessary ingredients for these exciting next steps."

Cheuk agrees that demonstrating the entanglement of molecule pairs is only the beginning of what's possible. The next phase, he says, is scaling that process and extending the work toward larger systems, such as chains of molecules.

"By using the building block of entanglement we have [already] demonstrated," Cheuk says, "we're excited to perform new experiments in the area of quantum simulation. In quantum simulation, the idea is that it's a bit like an analog quantum computer geared toward solving particular quantum physics problems. These problems are fundamentally important because they can, in many instances, describe the behavior of certain kinds of materials, including magnets and superconductors."

Holland credits Cheuk, who serves as his faculty adviser at Princeton, for his active role in the research process, for sharing his experience and knowledge in the realms of ultracold molecules and quantum simulation, and for the technical expertise he brought to building the infrastructure for the lab where the breakthrough took place.

As a physics professor who teaches both undergraduate and graduate students, Cheuk thrives on the open-ended nature of research and the unexpected surprises that can come along with targeted research goals.

"We're always pushing the frontier in controlling nature," he says. "In our case, we're trying to control molecules to a level that no one has done before. Oftentimes, while we are along this path of exploration, the picture of what's going on is unclear. But as you progress, things start clearing up, and every now and then we make a new discovery. This process is quite fun because the rules themselves are not set by anyone but nature, and we often have to figure out how to use these rules to reveal the essential physics at work."