Schrödinger's Killer App: Quantum Technology at LSU

By Jenny Linscott and Paige Brown

LSU is well-known for leading the field in a number of different areas, from environmental science, to engineering, to ecology, to materials science, to football. But LSU is a hotbed for another field that remains mysterious to most of us in our daily lives: quantum technology.

Imagine a computer that could solve a mathematical problem larger than the number of all the atoms in our universe, a sensor that could read pilots' minds to steer a plane, or a Doppler sensor sensitive enough to detect individual raindrops in a hurricane. What do all of these futuristic devices have in common? The answer is quantum technology, a field of physics and engineering that applies some of the stranger features of quantum mechanics to computing, cryptography, and sensing.

The term "quantum technology" was coined by LSU physics professor Jonathan Dowling, author of a new book—*Schrödinger's Killer App*—that documents the ongoing race to build the world's first quantum computer. Dowling is co-chair of the Hearne Institute of Theoretical Physics at LSU, where his work lays the foundation for quantum computers that could one day vastly outperform our current classical hardware. The man who has the term "qbit" imprinted on the license plate of his car is also helping to coordinate the work of a growing team of quantum technology researchers at LSU.

"We are becoming well known at LSU as a hotbed of quantum technologies," Dowling said. "And we are gaining a critical mass of quantum researchers to be able to tackle applications of quantum sensing and quantum computing."

Theoretically, quantum technology exploits quantum mechanics, or the rules that govern matter and energy at scales smaller than the atom. As scientists who study the physics of atoms and subatomic particles such as photons and electrons know, small particles behave in weird ways not observed at scales that the human eye can see.

"Any time you start talking about quantum mechanics, it's totally different from any other field of physics," said Joel Tohline, former director of the LSU Center for Computation & Technology (CCT).

Because subatomic particles such as photons can behave as both discrete particles and as continuous waves at the same time, they can interact in ways that allow them to store information in an almost infinite number of possible states. The weird wave-particle duality allows for more complex storage of information in quantum bits, or "qbits," than in classical computer information bits. While traditional computing bits are either "on" or "off," in one of two states, two photons can be engaged in a relationship known as quantum entanglement that allows them to encode many different possible states. Because of this greater potential for information storage, quantum computers could theoretically solve complex mathematical equations at a blistering speed.

"There are certain problems that are so complex, the computer resources needed would exceed the number of atoms in the whole universe," said Tohline. "But quantum computing brings in another element that does away with traditional limits. We are just beginning to build tiny versions of such quantum computers. It's technically very challenging, but the CCT is getting ready for the computer technologies of the future."

The race to the quantum computer is just one way that research in theoretical physics is shaping both technology and our understanding of the universe. LSU's tradition in this research is a strong one, beginning in the 1970s with groundbreaking work on the quantum properties of light.

Today, the tradition continues with the world-class Hearne Institute, created with an endowment from LSU alumnus Horace J. Hearne in 1994, and the CCT, which is working on building and supporting research groups in materials science and quantum physics at LSU. The co-directors of the Hearne Institute, Dowling and fellow LSU physics professor Jorge Pullin, are behind the Institute's two foci: quantum computing and quantum gravity. Mark Wilde, a new assistant professor with a joint appointment in the Department of Physics & Astronomy and the CCT, is also collaborating with Dowling to apply quantum technologies to computer science.

Quantum Computing

As Tohline explains, the CCT is looking to researchers like Dowling to help computer scientists prepare for the future of computer technologies. The CCT is always planning for the next revolution in supercomputing.

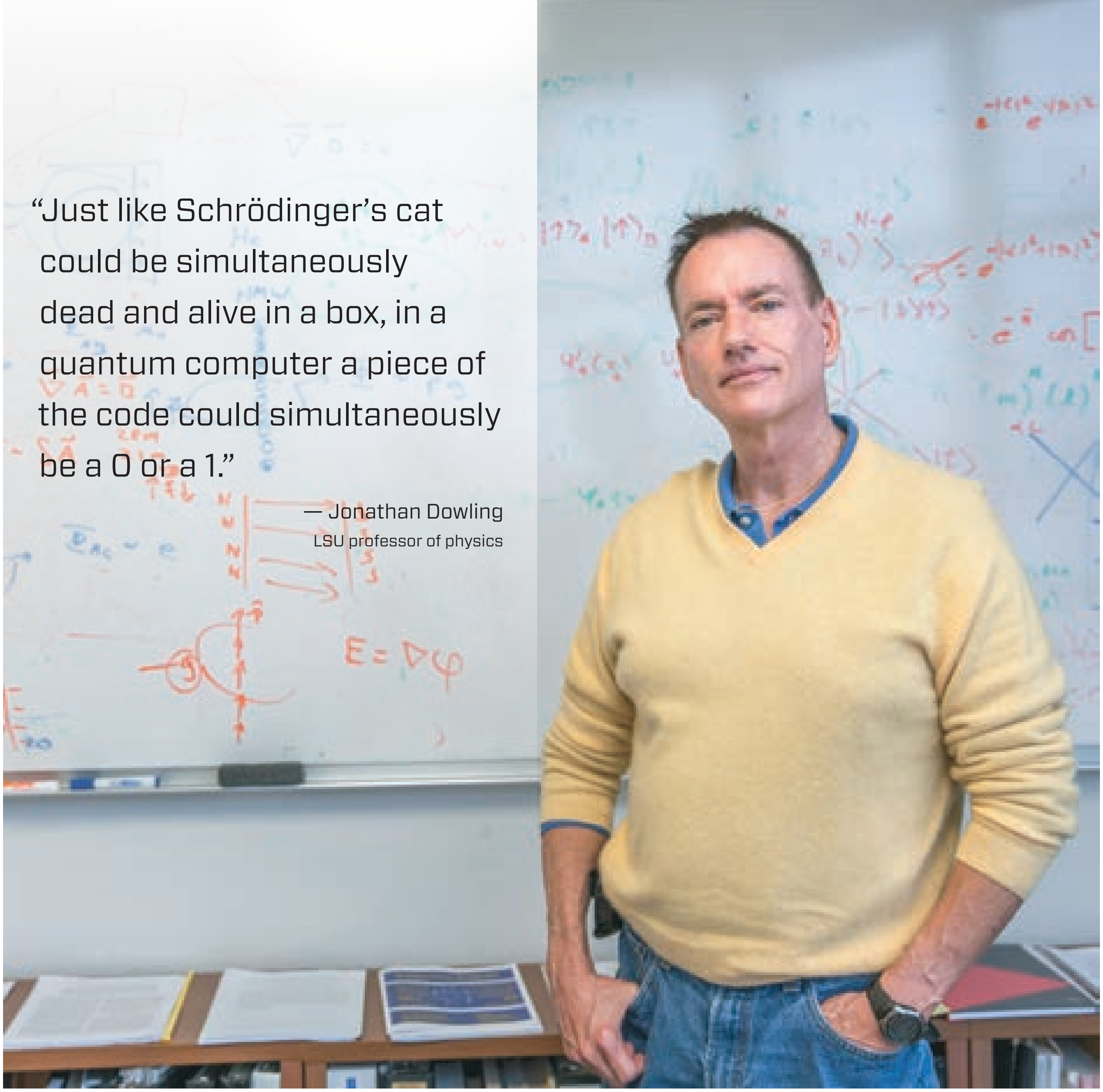
"Another 40 years down the road, quantum computing will be coming," Tohline said. "We are planning for that, and it's fun to be on the frontiers of this technology."

The promise of quantum technologies, Dowling explained, is a knack for long division. For example, Internet encryption today relies on the difficulty of long division to protect data like credit card numbers and bank transactions.

"Up until 1994, people thought long division, or factoring, was a hard problem on any computer," Dowling said. "This kept data safe because the codes use numbers so huge it would take longer than the lifetime of the universe to divide them out and crack the code. But in 1994, Peter Shore at Bell Labs built a mathematical proof to show that if you had a quantum computer, running on quantum physics, it could actually divide out long numbers very quickly. What would take your laptop longer than the life of the universe to divide out would take a quantum computer a fraction of a second."

At that rate, a quantum computer could make fast work of search functions, data analysis, and improved codes for encrypting Internet data, for example. But that kind of power is only possible if computers can think differently than they think today.

Classical computers operate on the principles of classical mechanics, the linear set of rules of Newton and Galileo. But when looking at the universe on the smallest scale, the rules of classical physics no longer



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>
> — Jonathan Dowling
> LSU professor of physics

apply. This is the bewildering world of quantum theory, where light can be simultaneously both a wave and a particle, and an electron can simultaneously inhabit all its possible positions. There, in a famous thought experiment, Schroedinger’s cat can be simultaneously dead and alive. It is these simultaneous “superpositions” that are key to the future of computing.

“In a quantum computer, we replace bits with quantum bits, or qbits,” Dowling said. “In the quantum computer, the quantum bit could be a 0 and a 1 simultaneously. Just like Schroedinger’s cat could be simultaneously dead and alive in a box, in a quantum computer a piece of the code could simultaneously be a 0 or a 1.”

Qbits would yield an exponential increase in processing power and an exponential speed up in problem solving. Imagine, for example, a classical computer and a quantum computer faced with the same long division problem. The classical computer sits in one universe deliberately trying out every possible answer, one by one, while the quantum computer rushes out into parallel universes, trying out every possible answer at the exact same time. When it finds the right answer, it rushes back—and the parallel universes with their wrong answers instantly vanish.

Quantum computers could also be tweaked to do things other than compute. For example, the hardware can work as a magnetic field, radar, or light sensors that are much more sensitive than classic hardware. Imagine a quantum MRI machine inside of his helmet that could scan a football player’s skull for injuries, instead of requiring magnets the size of an entire hospital room. Sensors traditionally have a signal-to-noise ratio—or the extent to which they can measure a signal above background noise—limited by the laws of physics. But qbits could raise the “ceiling” of signal-to-noise capability by operating at the subatomic level. It’s all about the quirky nature of quantum particles existing in multiple states simultaneously.

For quantum computers and sensors to move from mathematical proof to reality, however, qbits need to maintain their superpositions for long periods of time without collapsing into one state or the other. Because the culprit of collapse is usually heat from the environment, engineers will need to create highly advanced cooling systems and quantum error correction techniques that can replace the qbits that mistakenly collapse.

Wilde, collaborating with both Dowling and computer scientists at the CCT, has been working on devising a new quantum theory of information that could help make quantum computers a reality. Wilde currently teaches a course on quantum communications in the physics department at LSU.

"A lot of what I do is try to find out what are the fundamental limits of communication," Wilde said. "There has recently been a revolution in revising the laws of information and communication with quantum theories."

Wilde explained that while people currently use fiber optic cables that transmit photons for their Internet communication devices, current schemes of information storage and transmission don't incorporate the laws of quantum mechanics that govern the photons themselves. As photons increasingly become a promising source of quantum information storage, Wilde is working on creating algorithms that would protect this quantum information and correct for errors as photons are shuttled around inside of a computer.

"In a hundred years, it's very clear that we will have a quantum computer," Dowling said. "When it comes online is very hard to predict. It will be trial and error over a long period of time."

Quantum Gravity

Pullin, Hearne Institute co-chair, turns the insights of quantum theory onto another realm altogether: gravity. It's a meeting of two radically different theories.

"Quantum is the theory of small stuff," Pullin explained. "Gravity, on the other hand, is the theory of big stuff—stars, planets, the earth. These theories have developed separately, and we don't understand how they fit together."

Quantum gravity attempts to reconcile these two theoretical regimes, to understand how they fit together.

"That could help us understand what happened very close to the beginning of the universe," Pullin said. "Our universe expanded from a very small state, and therefore we need quantum theory to describe it. But we're talking about the whole universe, so you need gravity as well."

Pullin's work could also help to explain the great cosmological enigma of black holes, those ominous regions of space that are dense, ominous deformations of space/time.

"We believe that inside black holes, matter is being compressed into a very small space," Pullin said. "You have a lot of matter there, so you need gravity, but it's a small space, so you need quantum."

The mathematical equations that we use to describe gravity today fail to describe black holes. There, the equations break down, producing a troublesome outcome called singularity—where the gravitational field seems to become infinitely strong and crushes matter to an infinite density. Quantum gravity, however, could describe the bizarre phenomena of black holes without resorting to the paradox of singularity.

Quantum gravity would also refashion the way researchers think of the texture of the universe. Modern descriptions come from Einstein and his vision of gravity as a deformation of space/time. Quantum gravity would actually quantize space/time, showing that it's made of elementary units just like matter is made of atoms.

"We're trying to build the equivalent of atoms for space/time," Pullin said.

Much like quantum computing, quantum gravity is still a theoretical horizon. But theory can yield very observable consequences. As Pullin explained, the history of physics is littered with examples of people discovering how two theories fit together and suddenly arriving at new predictions.

Pullin joined the LSU faculty as the first Hearne Institute Chair in 2001. Today, the quantum gravity research group is growing, drawn by LSU's history of quantum research and by experimental gravity projects nearby at the Laser Interferometer Gravitational-wave Observatory (LIGO) in Livingston, Louisiana, one of only two of the largest gravity wave detectors in the United States.

"Students are coming from all over the world to study quantum technologies at LSU," Dowling said. "All the pieces are here to punch through the glass ceiling of the classical laws of physics."