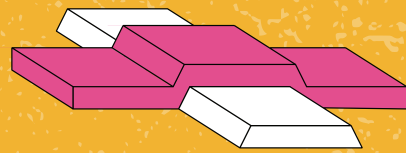
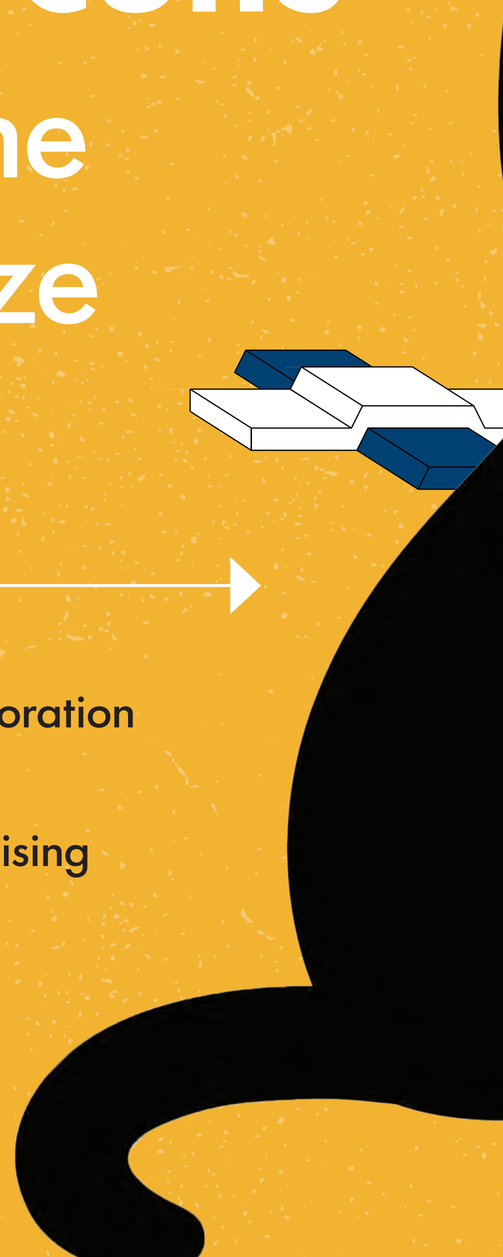


Superconducting quantum circuits

At the heart of the 2025 Nobel Prize in Physics

Johanna L. Miller

Although motivated by the fundamental exploration of the weirdness of the quantum world, the prizewinning experiments have led to a promising branch of quantum computing technology.



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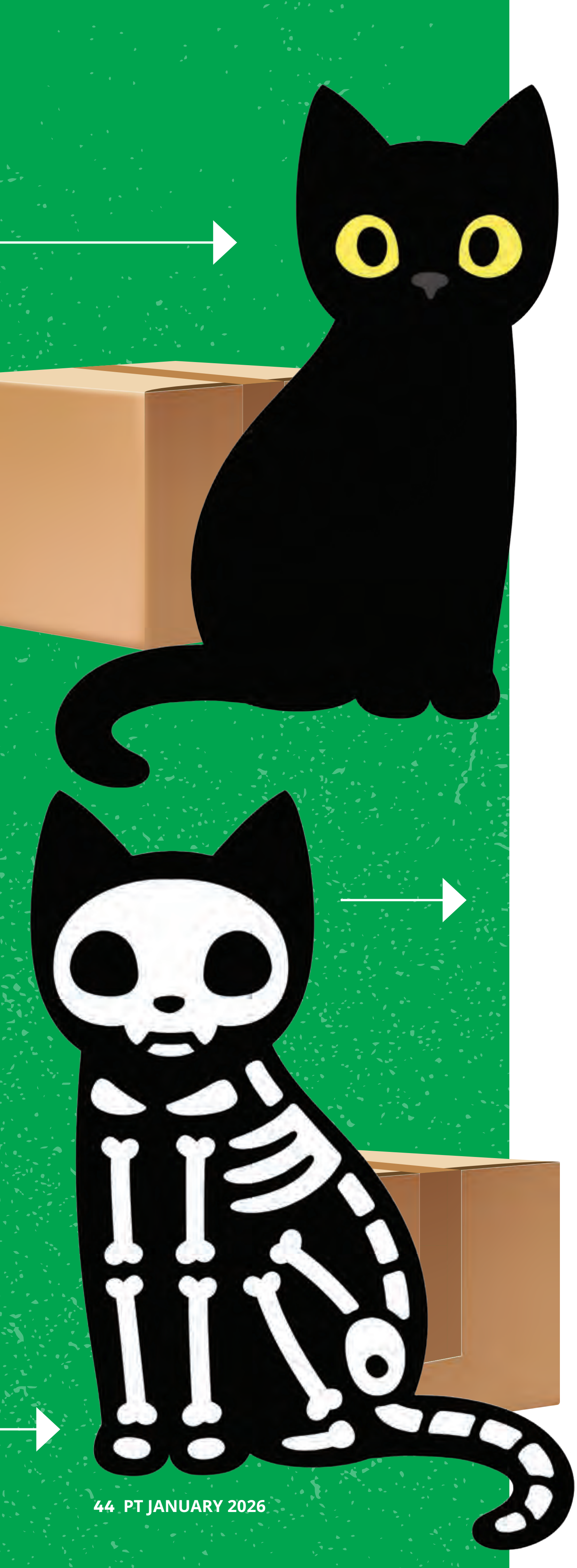


All cats, as far as anyone can tell, are either dead or alive—but atoms can be in two places at once. The crisp boundaries and deterministic behaviors we experience in the classical, macroscopic world seem at odds with the inherent fuzziness and randomness of quantum mechanics. From the early days of quantum theory, physicists have struggled to intuitively reconcile the quantum and classical realms and to locate the boundary between them, if one exists.

The 2025 Nobel Prize in Physics honors a series of landmark experiments[1–3] from the mid 1980s by John Clarke, Michel Devoret, and John Martinis (all, at the time, at the University of California, Berkeley) that convincingly demonstrated that quantum tunneling and energy-level quantization can occur in a millimeter-scale electronic circuit. The experiments are noteworthy less for their results—it would have been far more surprising if the circuits didn't obey the predictions of quantum mechanics—than for their ramifications. The laureates showed that the macroscopic quantum world could be brought under experimental control. And their work laid the foundations for the superconducting qubits that are at the cutting edge of quantum computing research today.

Posing the question

In one sense, "Why don't we see quantum effects in the macroscopic world?" is easy to answer: Planck's constant $\hbar$ defines a physical scale that, compared with most of what we encounter in our everyday experience, is small. Beginning students of quantum mechanics are often amused to find that they can calculate the probability of some classically absurd thing—walking through a wall, for example, or part of your left earlobe spontaneously appearing on Jupiter—and that that number is not identically zero. But it might as well be. The time it would take a human body to tunnel through a wall, multiplied by the energy barrier it would have to overcome to do so, is so large relative to $\hbar$ that the tunneling probability has a gargantuan negative exponent, and the event would never happen. (For some pandemic-era musings on other unphysical calculations, gargantuan negative exponents, and the meaning of "never," see the 2020 *PT* column "A pea, the Sun, and a million monkeys.")

In another sense, "Why don't we see quantum effects in the macroscopic world?" evokes a different easy answer: We do. The flow of persistent currents in superconductors is a quantum phenomenon. So is the photoelectric effect. So are the existence of crystals with well-defined facets and chemicals with well-defined colors. So is the mere existence of solid matter. The echoes of quantum mechanics in our everyday experience are not sparse. But in each case, the entities behaving quantum mechanically are atoms or subatomic particles, not macroscopic collective variables like the position of a bowling ball or a person. Microscopic quantum effects make themselves known at the macroscopic level, but a macroscopic system showing its own tunneling or energy-level quantization would be an entirely different thing.

In yet a third sense, the question becomes significantly more subtle. The time-dependent Schrödinger equation states that systems' wavefunctions evolve deterministically, and it makes no allowance for the probabilistic collapse of those wavefunctions during measurements. It would seem like any system set in motion would accumulate many superpositions of macroscopic states, of the type that Erwin Schrödinger highlighted with his eponymous cat paradox, that are never observed in the real world.

In a 1991 *Physics Today* feature article, "Decoherence and the transition from quantum to classical," Wojciech Zurek made the case that those superpositions are not observed because dissipation and decoherence conspire to destroy them. No real-world system is perfectly isolated from its environment, and all the minute couplings and exchanges of energy break down the coherence between widely separated parts of a wavepacket. In effect, they transform the spookily quantum "The cat is simultaneously alive and dead" into the familiarly classical "The cat is either alive or dead, but we don't know which." And because large systems have more channels for interacting with their surroundings than small systems do, their superpositions disappear far more quickly. Regardless of how completely that argument explains the nonexistence of dead-and-alive cats, dissipation certainly makes it harder to observe pure quantum behavior in macroscopic systems.

So the question becomes, Can one create a macroscopic apparatus that exhibits behavior described by a collective coordinate, with energy and time scales that are not large relative to $\hbar$, and that is also sufficiently decoupled from its environment that its quantum states don't decohere? And the answer, as of the early 1980s, was "Maybe."

Designing the experiment

The key to observing quantum behavior in a macroscopic coordinate was that the coordinate could be something other than the physical position of a particle: Tunneling through a classically forbidden barrier doesn't have to involve literally walking through a wall. (More recently, researchers have started to harness the quantum behavior of position coordinates in mesoscopic and macroscopic mechanical resonators. For some examples from *PT*'s archive, see the 2025 Back Scatter "A macroscopic qubit," the 2023 news story "Macroscopic mechanical oscillator is herded into a Schrödinger cat state," the 2015 news story "A quantum squeezed state of a mechanical resonator has been realized," the 2010 news brief "Quantum properties in the mechanical world," and references therein.)

To see what such a quantum macroscopic variable could look like, consider the circuit in figure 1(a): The

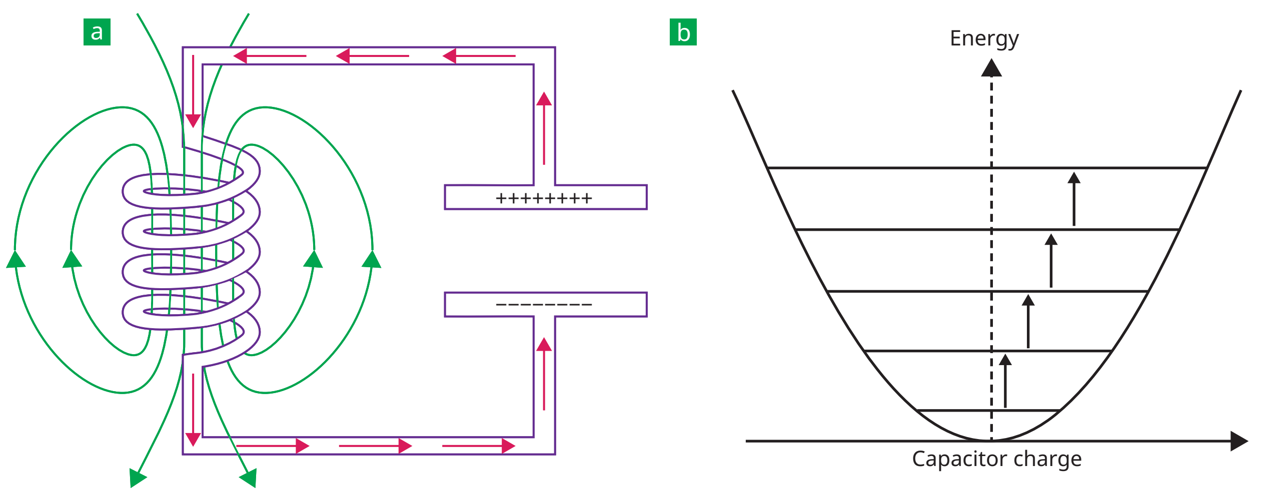


Figure 1. In an inductor–capacitor circuit **(a)**, charge bounces between the plates of the capacitor like a mass on a spring. The harmonic-oscillator potential **(b)** gives rise to a series of discrete energy levels. But because the levels are all equally spaced, observing their quantization would be difficult. (Figure by Freddie Pagani.)

state of the inductor–capacitor combination is characterized by the charge on the capacitor, which sloshes back and forth like a mass on a spring. The harmonic-oscillator potential, shown in figure 1(b), has equally spaced quantum states. As the laureates and colleagues have noted, with a temperature of 10 mK, an inductance of 350 pH, and a capacitance of 15 pF—all experimentally realizable values—the energy-level spacing would dwarf the system's thermal energy, and quantum effects would dominate.[4]

But how could you tell? You could try to observe the energy-level quantization by spectroscopically exciting transitions among the energy levels. But the levels are all equally spaced, and the frequency of transitions between them is equal to the circuit's classical resonant frequency, so there's no clear way to distinguish a quantum resonance from a classical one. Furthermore, there's no option to observe quantum tunneling, because with only one well in the energy potential, the system has nowhere to tunnel to.

Both those problems are solved with the switch from an inductor–capacitor circuit to a Josephson junction: two overlapping strips of superconducting material, as shown in figure 2(a), with a thin nonsuperconducting layer at the interface. Cooper pairs in the superconductors can tunnel through the interface—but importantly, the tunneling through that physical barrier is distinct from the macroscopic quantum tunneling that the laureates were seeking to demonstrate.

The state of the Josephson junction is characterized by the superconducting phase difference across the interface. That sounds like an exotic quantum mechanical quantity, but you can think of it as roughly analogous to the charge in the inductor–capacitor circuit: Both are macroscopic parameters that describe the collective state of all the charge carriers in the system. The phase difference is defined modulo 2π, and it follows a sine-wave potential rather than a parabolic one. The result, as shown in figure 2(b), is a series of energy levels that aren't equally spaced and plenty of energy barriers for the system to tunnel through.

If a Josephson-junction circuit is prepared in a low-lying state in one well of the sine-wave potential, classical physics would dictate that, barring any energy input into the system, it would stay there forever. But quantum mechanics predicts that the system has some probability of turning up in a different energy well: Despite lacking the energy to climb over the barrier, it can tunnel through it. And that tunneling probability can be made significant, even in a circuit that's not too small: In the one the laureates used, the interface between the superconductors was 10 μm by 10 μm. In a circuit of that size, tunneling through the energy barrier would involve the concerted motion of billions of Cooper pairs. Mathematically, it makes sense to describe their state as a single collective variable. But would that variable obey the Schrödinger equation, or would decoherence degrade or ruin its quantum behavior?

Clarke, Devoret, and Martinis weren't the first to appreciate that a Josephson junction could be an ideal

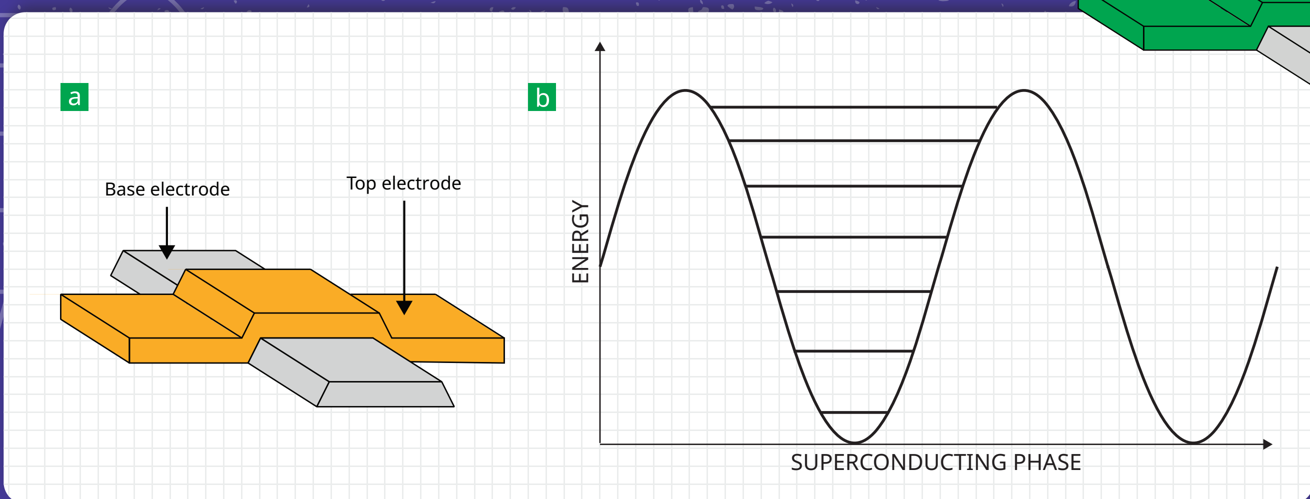


Figure 2. A Josephson junction **(a)**—two strips of superconductor separated by a thin nonsuperconducting interface—provided the ideal testing ground for macroscopic quantum effects. Its energy potential **(b)** is a sine wave, rather than a parabola, so its states are unequally spaced, and the system can tunnel from one energy well into another. (Panel (a) adapted from J. M. Martinis, M. H. Devoret, J. Clarke, "Quantum Josephson junction circuits and the dawn of artificial atoms," Nat. Phys. **16**, 234, 2020; panel (b) by Freddie Pagani.)

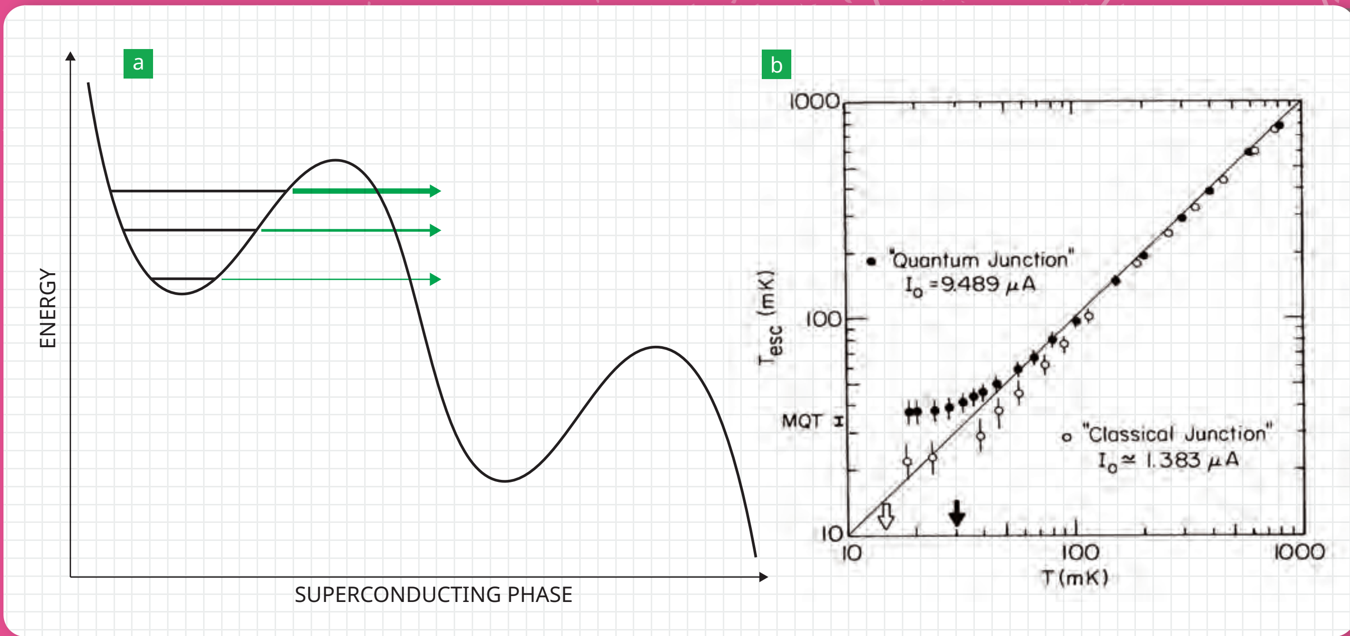


Figure 3. Applying a bias current to a Josephson junction transforms the flat sine-wave potential from figure 2 into a tilted one **(a)**. The system can then prove its quantum nature by tunneling out of the metastable energy well. The plot in **(b)**, from one of the laureates' landmark papers, shows one clear demonstration of the effect. The horizontal coordinate T is the system's real temperature, and the vertical coordinate T_{esc} is the temperature that would yield the observed escape rate if all the escapes happened classically. At higher temperatures the two are equal, but at lower temperatures they diverge: evidence of macroscopic quantum tunneling (MQT). (Panel (a) by Freddie Pagani; panel (b) from ref. 3.)

testing ground for macroscopic quantum effects.[5] Nor were they the first to attempt the experiment.[6] What set their work apart was the care with which they made their measurements—and, consequently, the clarity of their results.

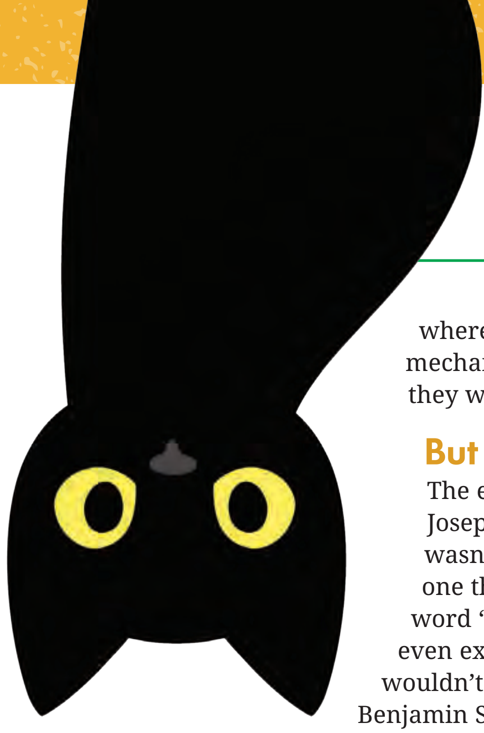
They started by thoroughly characterizing the circuit in the classical regime to pin down the parameters of the sine-wave potential—complete with error bars—and therefore the tunneling probability that they could expect under any given conditions. Because cooling to absolute zero is impossible, there was always some lingering probability that the circuit could get enough of an energy kick from the environment to hurdle over the barrier rather than tunnel through it. They needed to understand the likelihood of the first possibility to demonstrate the existence of the second.

For the test itself, the laureates biased the Josephson junction with a small current, which transformed the level sine wave of figure 2(b) into the tilted one of figure 3(a). Now the tunneling entity had somewhere to go: If it escaped the metastable state in the energy well it started in, it would go tumbling down the potential-energy hill, which would be observable as the spontaneous appearance of a voltage drop across the Josephson junction.

Starting at 1 K and cooling the system to progressively lower temperatures, the laureates measured how readily the voltage drop appeared. In the upper part of the temperature range, there was still plenty of thermal energy for the system to surmount the energy barrier classically. But as the temperature fell, the classical probability diminished. If the voltage drop kept appearing, it would have to be due to quantum tunneling.

Figure 3(b) shows one way of plotting their results. The horizontal axis is the actual temperature, and the vertical axis is the temperature that would yield the escape rate that they observed, assuming that all the escapes happened classically. In the upper right part of the plot, those temperatures are equal, but in the lower left, the effective escape temperature levels off while the real temperature continues to fall: clear evidence of tunneling.

In another series of experiments, the laureates used microwaves to excite the Josephson-junction circuit from the lowest metastable energy level to a higher one. Rather than varying the microwave frequency to home in on the quantum resonance, they varied the bias current, which changed the tilt and shifted the energy-level spacings. When it was in resonance with the microwaves, the circuit was excited to a higher energy level, which had less of an energy barrier to tunnel through, so the researchers observed the excitation as an enhanced escape rate from the metastable well. And the resonances always appeared



where quantum mechanics said they would.

But qubits?

The energy-quantized Josephson junction wasn't yet a qubit. For one thing, in 1985, the word "qubit" didn't even exist—and it wouldn't be coined by Benjamin Schumacher until a decade later, after Peter Shor discovered that a hypothetical quantum computer could find the prime factors of a large number faster than a classical computer could. The advent of Shor's algorithm helped launch the study of quantum information from a niche intellectual pursuit into something with potential real-world applications. (For more on the algorithm and its genesis, see the annotated version of David Zierler's interview with Shor published in *PT* in April 2025.)

For another thing, the Josephson junction still had more quantum properties to reveal. The laureates had demonstrated tunneling and energy-level quantization. But a useful qubit also needs the ability to be prepared in a superposition of states, which can be manipulated in conjunction with other qubits to create complex entangled states.

There are several ways to create superposable states out of a superconducting Josephson-junction-based circuit. *Physics Today* has covered superconducting qubits at several stages of their development: To read about them in more detail, see the November 2005 feature article "Superconducting circuits and quantum information," by J. Q. You and Franco Nori; the 2002 news story "Two realization schemes raise hopes for superconducting quantum bits"; and the 2009 news story "Superconducting qubit systems come of age."

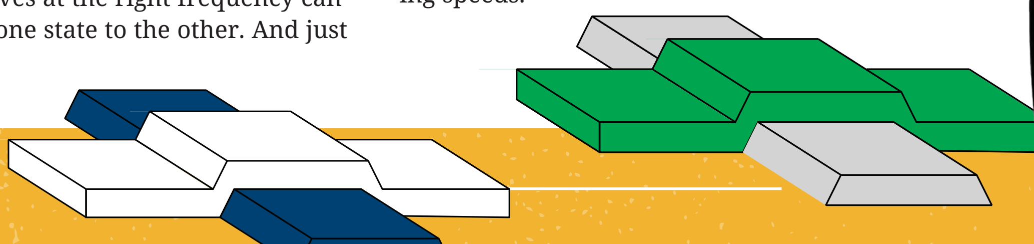
Perhaps the most conceptually straightforward of the superconducting qubits uses the lowest two energy levels of the system, as represented in figure 2(b), as the qubit's 0 and 1 states. The laureates had shown that a blast of microwaves at the right frequency can excite the circuit from one state to the other. And just like with other electromagnetically excitable systems, pulses of precise duration can partially transfer the system between the two states and thereby create any desired coherent superposition of 0 and 1.

That approach, called a phase qubit, was pioneered in 2002 by Martinis and others.[7] But it was pre-dated by a different scheme, called a charge qubit, in which Cooper pairs are made to tunnel one by one across a Josephson junction to an isolated superconducting island.[8] The states with some number n and $n + 1$ Cooper pairs on the island are designated as the qubit's 0 and 1 states.

A refined version of the charge qubit, called a transmon,[9] is currently favored by many quantum computing research groups. Transmons are the basis, for example, of the Google Quantum AI team's Willow chip, which recently achieved a long-sought milestone in quantum error correction. To counter the inherent delicacy of quantum states, researchers have hoped to build redundancy into a quantum computer by combining the states of many physical qubits to make one logical qubit. But that strategy works only if the physical qubits have a low enough error rate that adding more of them makes things better, not worse. And the Willow chip has done just that.[10]

But Google researchers aren't the only ones to be making great strides in quantum error correction and other prerequisites to practical quantum computation. Other teams are right on their heels, with implementations that use neutral atoms or trapped ions rather than superconducting circuits. It remains to be seen which qubits, if any, will be the building blocks of the quantum computers of the future.

Of the leading qubit contenders, superconducting qubits stand out in several ways. All qubits are quantum systems with discrete states, much like those of the atoms that occur in nature. And most qubits are either actual atoms or something similarly small. Superconducting qubits, however, are orders of magnitude larger—large enough to be connected with wires in much the same way as the components of conventional computing hardware are. And because they're engineered structures, their properties can be fine-tuned: Their interactions can be made far stronger and faster than those of natural-atom qubits, so they could potentially lead to faster computing speeds.



Understanding the answer

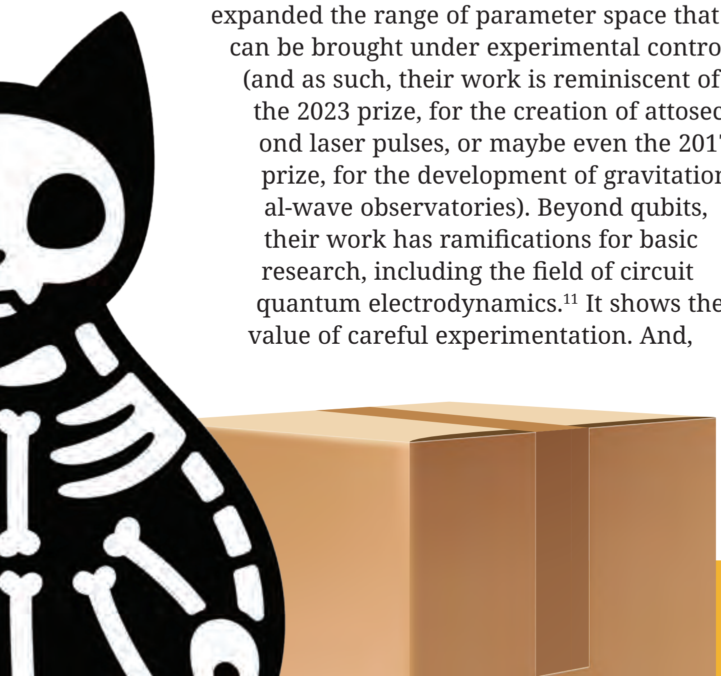
Despite recent advances, quantum computers are not yet a mature technology. In that respect, they stand in stark contrast to the neural networks—highlighted by the 2024 physics Nobel, covered in a December 2024 *Physics Today* news story—which are already having disruptive, world-changing effects throughout society, for good or for ill.

Of course, not every Nobel Prize in Physics is connected to a practical technology. The 2015 prize, for example, honored the discovery that neutrinos spontaneously change flavor as they travel (covered by *PT* in December 2015). Neutrino oscillations aren't the basis for any consumer products, and they probably won't ever be—although one never knows for sure.

But neutrino oscillations were an unexpected answer to a fundamental question about the universe. They're evidence that there's something going on in the subatomic world that's not well described by the standard model of particle physics, and they pointed toward places to look for answers to even deeper questions.

And that's not quite the story of the 2025 prize either. The fact that macroscopic collective variables obey the Schrödinger equation was, strictly speaking, not known for sure until it was observed. The observation did rule out some alternative theories that had been floated, such as the idea that above some suitably defined size scale, quantum mechanics just doesn't apply. But the results themselves weren't as revelatory as some years' prizes are.

No one who's not on the Nobel Committee can be sure of the reasoning for awarding any particular prize. But the value of the work by Clarke, Devoret, and Martinis seems to be in its effects on how physicists do physics. Their experiments expanded the range of parameter space that can be brought under experimental control (and as such, their work is reminiscent of the 2023 prize, for the creation of attosecond laser pulses, or maybe even the 2017 prize, for the development of gravitational-wave observatories). Beyond qubits, their work has ramifications for basic research, including the field of circuit quantum electrodynamics.[11] It shows the value of careful experimentation. And, through its implications for quantum computation, it may still change the world.



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