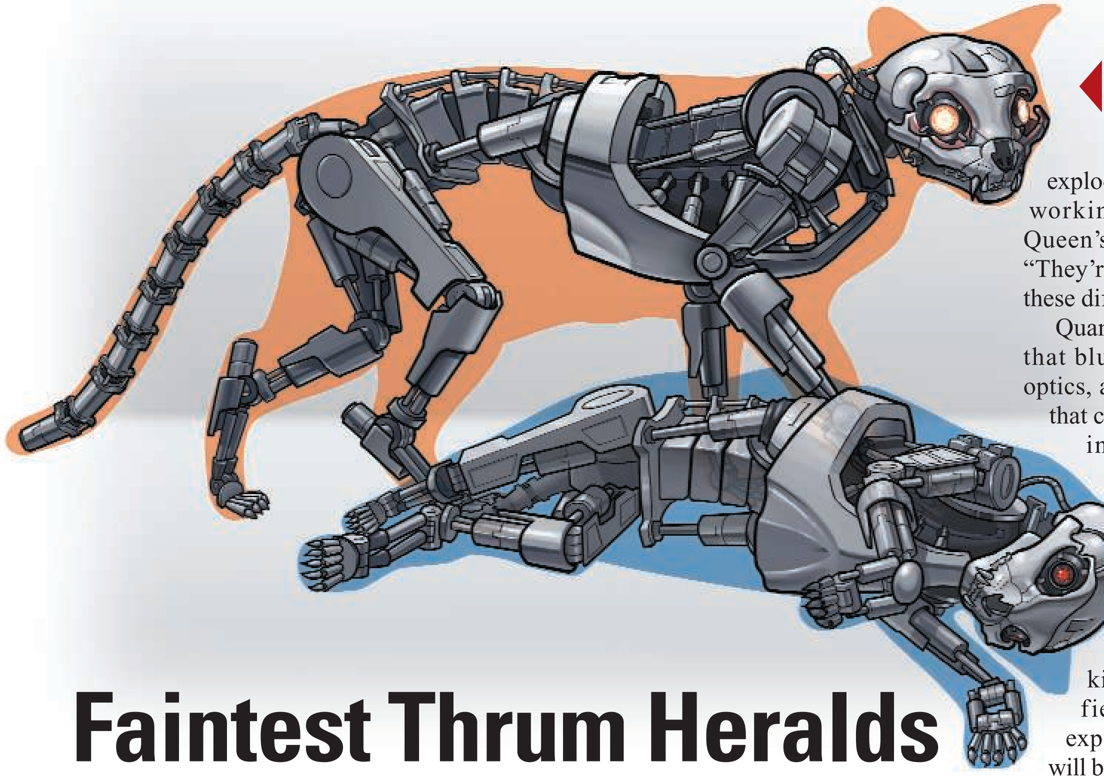

Meow. A gizmo occupying two places at once would be an analog to Schrödinger's dead-and-alive cat.

Faintest Thrum Heralds Quantum Machines

After years of trying, physicists are on the verge of making tiny vibrating devices that make the slightest possible movement. Far weirder mechanical devices could follow

IF YOU WANT TO BE REMEMBERED, MAKE A bad prediction. In 2003, *Science* reported that within 6 months physicists might create tiny machines whose movement obeyed the weird rules of quantum mechanics, which state that an object can absorb energy only in discrete "quanta" and can be in two places at once (*Science*, 3 January 2003, p. 36). That didn't happen, but Tobias Kippenberg, an experimenter at the Swiss Federal Institute of Technology, Lausanne, still shows a slide of the article in his talks. "It's entertaining, and it also reminds people exactly how challenging the problems are in this field," Kippenberg says.

Those obstacles are not insurmountable, however. Kippenberg's team and several others have nearly entered the realm of quantum motion. Ironically, to get there, they're racing to make gizmos that make literally the slightest movement, vibrating widgets drained of every possible bit of energy and quivering with only an unquenchable "zero-point motion." Recent progress toward that "ground state" of motion has come so fast that even Kippenberg is willing to prognosticate: "I expect in the next year there will be maybe a half-dozen groups observing this," he says.

If so, then the age of quantum machines will finally have arrived. Molecules, atoms, and subatomic particles all obey the mind-bending dictates of quantum theory. But physicists have never observed such odd behavior in the movement of a humanmade object. So their first goal has been to put the simplest machine—a vibrating beam or some other "oscillator"—into its ground state, which would be a crucial first step toward machines that oscillate around two different positions at once and other weird states of motion. Within the past 6 months, four different groups have come within a few dozen quanta of that goal, and researchers say one may have reached it.

Online
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Podcast interview with author Adrian Cho.

Curiously, as physicists have homed in on their objective, the field has grown more diverse. Seven years ago, a few groups of condensed matter physicists were pursuing a single strategy for reaching the ground state. Now, teams from optics and astrophysics have joined the chase. "The field has exploded in terms of the number of people working in it," says Robert Knobel of Queen's University in Kingston, Canada. "They're bringing their toolboxes from all these different fields."

Quantum machines could lead to devices that blur the lines between electronics, optics, and mechanics—humming widgets that coax light into odd states or translate information encoded in quantum states of photons into electronic signals. They might even probe a fundamental mystery: Why don't human-scale objects behave quantum mechanically? Reaching the ground state of mechanical motion is "the kind of result that will create a new field in itself," says Jack Harris, an experimenter at Yale University. "This will be a door opening—a big one."

High frequencies and low temperatures

But first physicists must make machines that make the slightest movement. Twentieth century physicist Werner Heisenberg's famous uncertainty principle implies that, like a small child, no object can stand perfectly still. Even in its ground state, it must possess a last, inextricable half-quantum of energy and jiggle with zero-point motion. Physicists would like to see that minimal tremor in a mechanical widget. To spot it, they are tinkering with nanometer-sized beams of semiconductor, micrometer-sized bits of glass, and even mirrors weighing kilograms.

Those objects all share a key property: When each is nudged away from its equilibrium position or shape, it oscillates at a well-defined frequency like a tuning fork. Quantum mechanically, such a "harmonic oscillator" can absorb energy only in quanta whose size is proportional to its frequency. So to reach the ground state, physicists need to extract all but the last, irretrievable half-quantum. That's easier said than done. Each quantum is so small that to remove them all, researchers must lower the oscillator's temperature—and hence its energy—nearly to absolute zero.

Nevertheless, physicists tried the direct route to the ground state. To make the energy quanta as large as possible, they etched beams of semiconductor that vibrated at high frequencies—up to 1 billion cycles per second, or 1 gigahertz. To make the beams

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as cold as possible, they relied on so-called passive cooling: sticking them in the best liquid-helium refrigerators, which can reach a few millikelvin, or thousandths of a degree above absolute zero. To sense a beam's motion, they employed a scheme called "capacitive coupling," applying a voltage between the beam and an electrode (see diagram). The beam's motion causes the voltage to vary.

Researchers ran into a few roadblocks, however. To push the frequencies of their vibrating beams higher, experimenters made them ever stiffer. But that meant that the size of the beam's already minuscule oscillations decreased even further, making them difficult to detect.

The scheme for measuring the beam's motion actually jostled the beam as well. Physicists tracked the varying voltage by observing how it affected the current through a device called a single-electron transistor. But as the electrons hopped through one by one, they tugged on the beam, creating "back action." "This back action is quite a bit bigger than you need for these quantum measurements," Knobel says. "And I don't think we understood that theoretically or experimentally at the time."

Cool new ideas

Even as the straight path to the ground state proved difficult, new avenues toward that goal began to open. In particular, experts in quantum optics began experimenting with techniques to control the motion of micrometer-sized objects with laser light. "It turns out that you can use the whole quantum-optics toolbox to prepare, manipulate, and read out a mechanical system," says Markus Aspelmeyer, a physicist at the University of Vienna.

Ironically, physicists can cool an oscillator by shining light on it. Conceptually, such active cooling works as follows: Researchers put a tiny mirror on an oscillating beam (see diagram). It and a larger, fixed mirror form an "optical cavity" that resonates with light of a frequency set by the mirrors' spacing, just as an organ pipe whistles at a pitch set by its length. If the little mirror could not move, then only light of this frequency could shine through the large mirror and into the cavity.

But if the mirror oscillates at a definite frequency, then laser light whose frequency has been lowered by that amount can also enter the cavity. To do so, however, each photon must absorb a quantum of energy from the mirror to make up for the energy it is lacking. So that "detuned" light saps energy from the oscillator. The light wave reemerging from the cavity also reveals the mirror's motion through shifts in the alignment of its peaks and troughs, or "phase," allowing researchers to detect the motion with greater sensitivity.

Using such "resolved-sideband cooling," three groups have reduced the energy of a micrometer-sized oscillator to between 32 and 67 quanta, as they reported in July 2009 in *Nature Physics*. The experiments varied in details. Aspelmeyer's team used a mirror on a beam; Kippenberg's shined light into a glass ring that served as both optical cavity and oscillator. Hailin Wang's team at the University of Oregon, Eugene, used a glass bead in a similar way. All three worked in fridges that reached a few kelvin; they think they can reach the ground state by starting at millikelvin temperatures. "It doesn't look like we are bumping into any fundamental issues" that prevent it, Aspelmeyer says.

Physicists working with nanometer-sized oscillators have found better ways to chill and measure their devices, too. In fact, they've borrowed the concept of resolved-sideband cooling. For example, Keith Schwab of the California Institute of Technology (Caltech) in Pasadena and colleagues have applied it to a silicon-nitride beam 30 micrometers long and about 150 nanometers thick and wide that thrums at 6.3 megahertz.

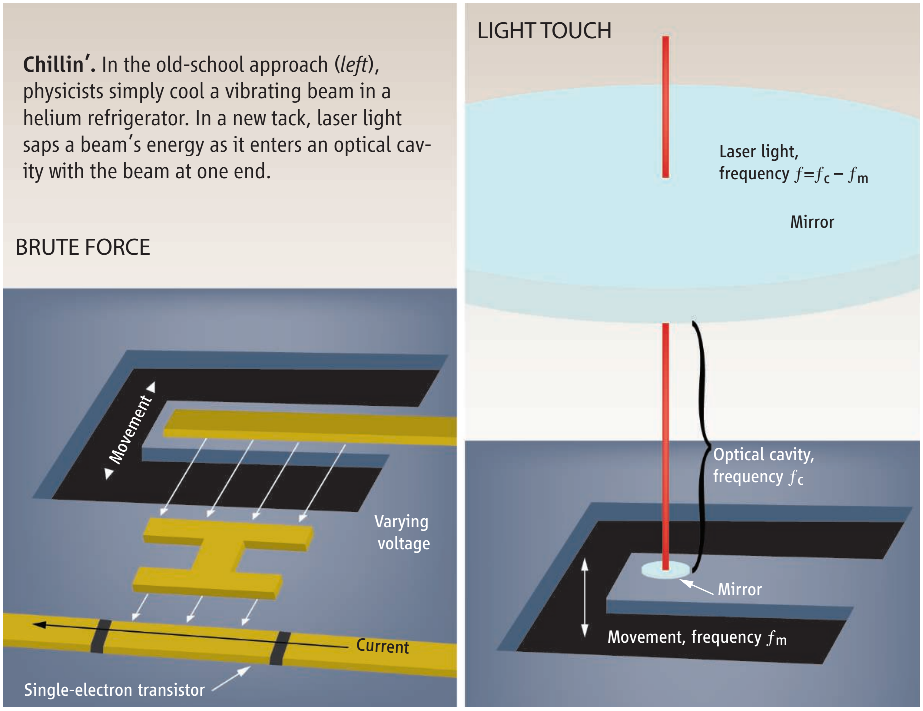
The beam couples to a nearby microwave resonator—simply a long strip of superconducting niobium that can ring with microwaves of a particular frequency. As in the optical experiments, detuned microwaves can enter the niobium strip only by absorbing energy from the beam. Starting at millikelvin temperatures, the researchers reduced the beam's energy to a handful of quanta, as they reported this month in *Nature*. "We pushed the experiment as hard as we could, and in the end we came down to four," Schwab says.

Brute force carries the day

In the race to the ground state, however, the straightforward approach seems to have won out. Andrew Cleland, John Martinis, and colleagues at the University of California, Santa Barbara, have succeeded by using a "brute force" combination of passive cooling and a very high oscillator frequency, say several physicists who have seen preprints describing the work. The key to the experiment lies in a clever scheme to detect the oscillator's motion, they say.

Cleland and Martinis's gizmo is a beam that vibrates at a whopping 6 gigahertz, researchers say. But rather than swinging up and down, it gets thinner and thicker. It also consists of so-called piezoelectric material that creates an oscillating electric field as it expands and contracts, making that motion easy to detect.

To do that, Cleland and Martinis rely on a widget called a "phase qubit," a strip of superconductor with a nonsuperconducting patch in it that acts a bit like a sandbar in a stream of free-flowing electrons. The details aside, the phase qubit is itself a highly controllable quantum-mechanical system with a



Chillin'. In the old-school approach (*left*), physicists simply cool a vibrating beam in a helium refrigerator. In a new tack, laser light saps a beam's energy as it enters an optical cavity with the beam at one end.

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ground state and one higher-energy state. Researchers can ease the qubit from one state to the other—or even put it into both states at once—by applying microwaves of a specific frequency. Moreover, they can change that frequency by adjusting the current flowing through the qubit.

So Cleland and Martinis can feed energy quanta into the oscillating beam one by one. They first put the qubit into its energetic state and then adjust the qubit's frequency to match that of the oscillator to shuffle the quantum of energy over. They can also run the process backward to pull quanta out of the oscillator. And the team has pulled out every last one to reach the ground state, others say. "I would say that Andrew and John have achieved it," Schwab says. "We've gotten damn close, but these guys are deep into it."

Cleland and Martinis had previously used a phase qubit to fiddle with a microwave cavity. They showed they could put the cavity into any delicate quantum state, including the ground state or one in which it contained two different numbers of microwave photons simultaneously, as they reported in May in *Nature*. Now, they have simply replaced the gigahertz microwave cavity with a gigahertz mechanical oscillator, others say.

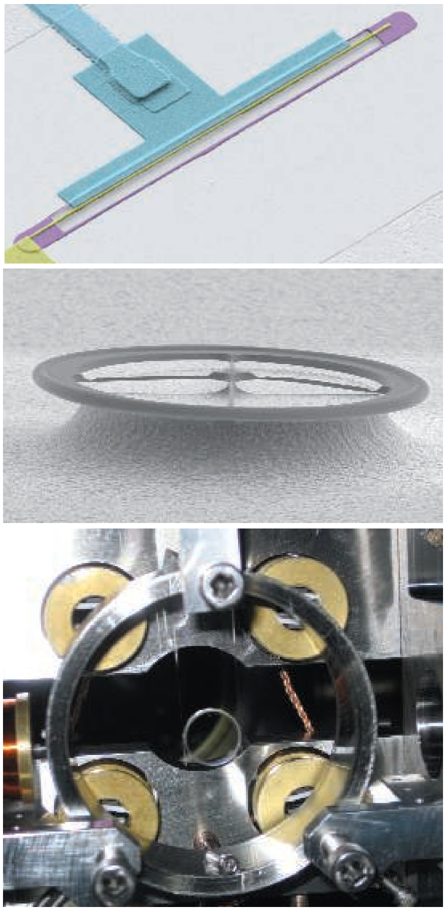
Not everyone is convinced that the Santa Barbara team has reached the desired goal. The researchers detect not the motion of the beam but the electric field the material produces, Kippenberg argues: "It's not a purely mechanical oscillator." The experiment could be done with a different material that would produce such a field through internal stresses, without mechanical motion, he says. Others say that's a quibble, as the Santa Barbara device does move.

Testing the limits of reality

Just what quantum machines will be good for remains to be seen. Most immediately, they might have technical applications in basic research. A gigahertz nanomechanical oscillator in its ground state would make an exquisitely sensitive force detector, says physicist Konrad Lehnert of JILA, a laboratory run jointly by the National Institute of Standards and Technology and the University of Colorado, Boulder. "That gives you a way to interrogate the nanoscale world in a very gentle, noninvasive way," he says.

Micrometer-sized widgets in quantum motion might prove particularly useful in quantum optics experiments, says Yale's Harris. They might serve as "nonlinear" optical elements that perform tasks such as splitting a single higher-energy photon into two lower-energy ones, he says. Currently, researchers do such things by passing light through certain crystals, which typically absorb a large fraction of the photons. Quantum machines might do the job without such high losses, Harris says.

The tiny machines might also bridge the gaps between various technologies. Physicists can already control the quantum behavior of electrons and of electromagnetic waves such as light or microwaves. Quantum machines would enable them to control quantized vibrations, or "phonons," and forge connections among all three, says Oskar Painter, an applied physicist at Caltech. "You've got phonons, photons, and electrons" working together, he says. "That's where the revolution is going to come from."



Many sizes. Physicist are experimenting with nanometer-sized beams (*top*), micrometer-sized rings (*middle*), and macroscopic mirrors.

Painter is already pushing in that direction. His team recently fashioned a beam of silicon 30 micrometers long and 1.4 micrometers wide and patterned it with a ladderlike arrangement of holes. The pattern simultaneously traps light and vibrations. In fact, the pressure from trapped light can set the beam vibrating, and that motion reveals itself in microwaves emanating from the beam, the team reported in October 2009 in *Nature*. Such a structure could convert optical signals to microwaves and vice versa, Painter says.

Quantum machines might ultimately probe the origins of everyday reality. Although the rules of quantum mechanics allow an object to be in two places at once, human-sized "classical" objects do not behave that way. "Systems either behave quantum mechanically or classically," says Nergis Mavalvala, an astrophysicist at the Massachusetts Institute of Technology in Cambridge. "Is there something murky in between? I don't think anyone has an answer for that."

Many physicists think that in principle a large object could be put into such a two-places-at-once state—if it were shielded from vibrations, radiation, and other environmental influences, which cause such delicate states to "collapse." Others argue that as-yet-unknown factors may prevent large objects from behaving quantum mechanically. Famed British theorist Roger Penrose argues that if a large object were put into a here-and-there state, its own gravity would pull it to one place or the other, taking the quantum weirdness—and perhaps some of the fun—out of the everyday world.

To test such ideas, many researchers would like to try to put a human-sized object in two places at once. "There's nothing better than an experiment that proves that it works or it doesn't," Mavalvala says. Such experiments are a ways off, but physicists are surprisingly close to reaching the ground state of a jumbo oscillator. Using optical techniques, Mavalvala and colleagues cooled a 1-gram mirror to 100,000 quanta, as they reported in 2007 in *Physical Review Letters*.

More recently, the group has cooled mirrors weighing 10.8 kilograms even further. The four mirrors form two crossed 4-kilometer optical cavities in the Laser Interferometer Gravitational Wave Observatory (LIGO) in Hanford, Washington, which is designed to detect ripples in spacetime. Using LIGO's electronic stabilization system in lieu of lasers, the team cooled the mirrors' relative motion to just 234 quanta, as they reported in July 2009 in the *New Journal of Physics*.

Exactly where quantum machines will lead may be impossible to say. But once physicists can put gadgets into quantum motion, the possibilities may be limited only by researchers' ingenuity. Something new and wild seems sure to shake loose.

–ADRIAN CHO

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