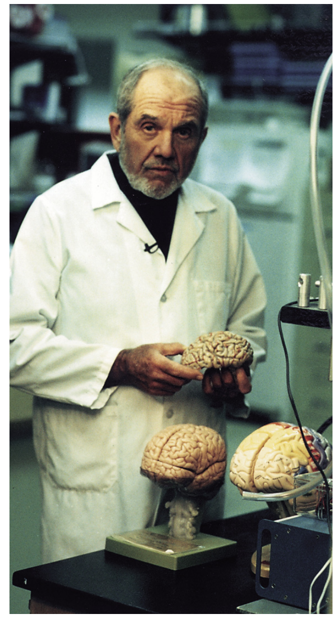
Caltech's Newest Millionaire

At least until the next IPO, Caltech's newest millionaire is Joseph Trela (BS '97), who on March 23 took Regis Philbin all the way on the hit TV quiz show *Who Wants to be a Millionaire?*, becoming only the third contestant ever to have done so. (In case you've been living under a rock, *Millionaire* players answer progressively harder questions to win increasing sums up to $1,000,000.) Contestants are allowed to "Phone A Friend" once during the taping if they get stumped, and, says *The California Tech*, "a mob" of residents of Trela's old house, Dabney, were standing by the lounge phone to take his call. Although the Darbs never made it on the air, Professor of Literature Jenijoy La Belle did when he said that she'd "be very disappointed in him" if he blew the source of the quote, "The first thing we do, let's kill all the lawyers." (He did not let her down, correctly citing *Henry VI, Part II*.) And, fittingly for a Techer, his million-dollar question was to name the insect that shorted out an early supercomputer and inspired the term "computer bug"—moth, roach, fly, or Japanese beetle. (It's a moth.)

So what's he going to do with the money? Oh, the usual—pay off his student loans, put his brother through Notre Dame, take some time off…

Right: The day the episode of *Millionaire* aired, PBS was on campus taping "The College of Comedy with Alan King" for *Great Performances*. (In fact, King thanked the crowd that packed Beckman Auditorium for coming to see him rather than staying home to watch that other show.) In the introductory segment, taped in Rosen Professor of Biology Scott Fraser's lab, King picks his brain before doing his shtick.



Left: Caltech's oldest millionaire, Life Trustee and Chair Emeritus Arnold Beckman (PhD '28), turned 100 on Monday, April 10. The preceding weekend, Caltech's Beckman Institute hosted a symposium highlighting research at the interface of chemistry and biology—a conjoining that Beckman left his mark on. On the day itself, Caltech threw a black-tie gala, including fireworks, in his honor. Here he prepares to blow out the candles on his birthday cake, shaped in the likeness of Beckman Auditorium—one of four buildings on campus to bear the Beckman name—as President Baltimore cheers him on.

In other food-related news, Luke Wang (PhD '97) shot the picture at left at the Universal Studios theme park in Florida. In case you can't read it, the drum says "Home of the BIG ONE." And the canned pork product below, spotted on the shelves of a local grocery store, is the first luncheon meat that also detects gravitational waves. (It's distributed by the Liberty Gold Fruit Company of South San Francisco, hence the name.)

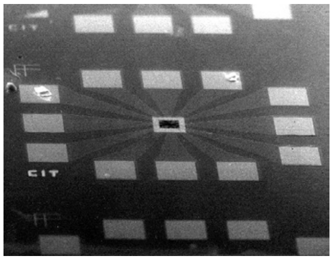
You Can't Beat This Heat

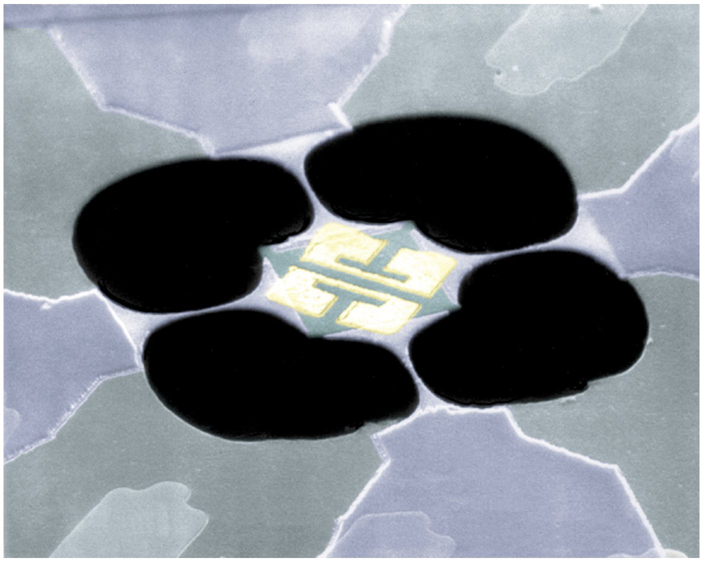
A team led by Professor of Physics Michael Roukes has announced the first observation of the quantum of thermal conductance. This discovery reveals a fundamental limit to the heat that can be conducted by objects of atomic dimensions. The findings, reported in the April 27 issue of *Nature*, could have profound implications for the design of microscopic electronic devices and for the transmission of information, says Roukes.

Heat flows through a solid object by means of collective wavelike vibrations of its atoms. These waves are called phonons after the fashion of electrons, protons, photons, etc., but based on the Greek root, *phon*, for sound. Usually immense numbers of phonons, each inducing a unique type of synchronous motion of the atoms, act simultaneously. In the everyday world, each phonon is just one among a sea of zillions—its contribution is imperceptible, and variations in heat flow appear to be smooth and continuous, not incremental.

But in the nanoworld, the phonon sea is finite—more of a pond, really. Quantum effects rule, and heat conduction can become radically different. When an object at temperatures close to absolute zero becomes extremely small, only a limited number of phonons play a significant role in heat flow within it; most types of motion become "frozen out," leaving the heat to be carried by the few modes that persist. Unlike a quantum of light, or photon, which is the minimum package of light energy that can exist, a quantum of thermal conductance is the maximum amount of heat energy that can be carried by a phonon mode. The Roukes team has demonstrated that this conductance depends only on a handful of fundamental physical constants and the absolute temperature itself, regardless of the solid—in other words, at this level, asbestos conducts heat as efficiently as copper. (For the physicists in the audience, the conductance equals $p^2k^2T/3h$, where k is Boltzmann's constant, T is the absolute temperature, and h is Planck's constant. At an ambient temperature of one kelvin, this translates into 9.4×10^{-13} watts of power per kelvin of temperature rise.)

To measure such minute changes, former Sherman Fairchild Distinguished Postdoctoral Scholar Keith Schwab, the *Nature* paper's lead author and now at the National Security Agency and the University of Maryland, fabricated tiny devices with specially patterned features only 100 billionths of a meter across—about 300 atoms wide—with assistance from then-research staff member Erik Henriksen, now at Columbia University, and in collaboration with visiting associate John Worlock of the University of Utah. The group's three-year effort followed on the work of Thomas Tighe, a previous postdoctoral fellow in the





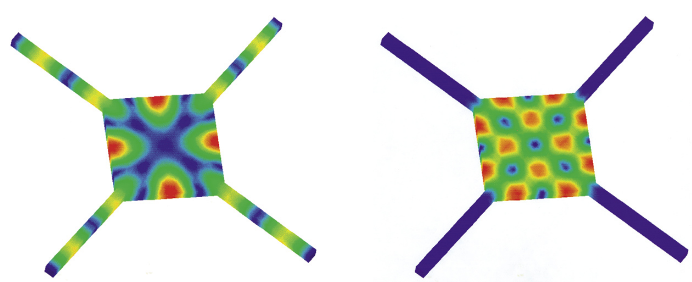
Left: An overall view of the roughly 1.0 × 0.8 millimeter device, showing the 12 wirebond pads that converge, via thin-film niobium leads, into the central 60-nanometer-thick silicon nitride membrane, which appears dark. Below: The suspended 4 × 4 micron "phonon cavity" (center) is patterned from the membrane, which has been completely removed in the dark regions. The bright C-shaped objects on the cavity are the thin-film gold transducers—the "electron puddles"—which are connected to the thin-film niobium leads that run atop the "phonon waveguides" to the wirebond pads. The waveguides neck down to less than 200 nanometers wide.

group, and culminated in new techniques for creating the devices out of silicon nitride. At the heart of the device is an isolated heat reservoir, called a "phonon cavity," which is a miniature plate freely suspended by four narrow beams. Each beam acts as a quasi-one-dimensional "phonon waveguide" for heat flow. On top of the cavity, Schwab and Henriksen deposited two thin-film patches of gold, described by Roukes as "puddles of electrons." One puddle is used as a heater; the other as a thermometer. To escape from the suspended cavity, the heat must flow through the waveguides. Meanwhile, the cavity saturates at a higher temperature that directly reflects the waveguides's thermal conductance. (The puddles' electrical leads, which run atop the phonon waveguides, are made of superconducting material since the thermal conductance of an ordinary metal would thermally "short out" the measurements.)

Measuring this temperature rise (typically a few millikelvins at a temperature of 100 millikelvins) was a significant challenge in its own right. Most thermometry techniques involve electrical power levels that would have overwhelmed the measurements. "We used about a femtowatt of power to heat the cavity, which is roughly what your eye would receive from a 100-watt light bulb 60 miles away," says Schwab. So the researchers coupled the second "electron puddle" to extremely sensitive dc-SQUID (superconducting quantum interference device) circuitry that allowed them to measure the feeble current fluctuations whose magnitude is directly proportional to absolute temperature. (This so-called Johnson-Nyquist noise is also the origin of the electrical noise that causes the background hiss in audio systems.) Because the researchers know the precise amount of heat deposited, and can directly measure the absolute temperature reached by the cavity in response, they can calculate the thermal conductance of the waveguides.

Since this conductance is independent of the material, the only way it can be increased in a very small device is to make the conductor larger, which has important implications for nanotechnology as well as for the transmission of information. Each individual transistor on a microchip gives off a little heat, which becomes a significant problem when millions of such transistors are placed in close proximity. "This will become especially serious for future molecular-scale devices," says Roukes. "No matter how small a device is, you always have to put a finite amount of power into it to turn it on. In the quantum regime, when only a limited number of modes are capable of transferring heat, it will be crucial to take this fundamental limitation into account."

Theoretical studies carried out elsewhere indicate that the maximum thermal conductance is linked to the maximum rate that information can flow into a device having a single quantum "channel"—a manifestation of a deep connection between information and entropy. "As we engineer smaller and higher speed computational elements, we will also encounter this fundamental quantum limitation in the rate of information flow," says Schwab. □—*RT*



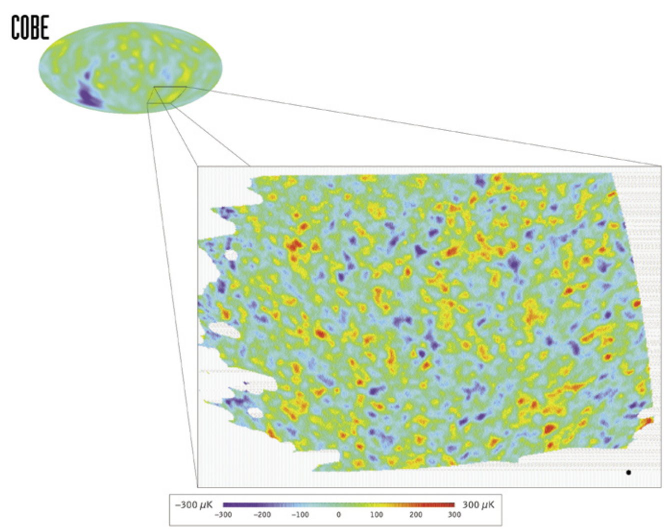
In these simulations of phonon vibrational modes by grad student Darrell Harrington, red represents high local strain amplitude and violet is low. At left is a mode that includes the waveguides and thus allows the cavity to cool. At right is a localized mode in which the waveguides are quiescent (violet) and cannot directly transfer energy to the outside world.

There's an outdoor showcase for experimental art on campus now, tucked in behind the recycling center on Holliston Avenue. The location is particularly apt for the latest work, Economic Icon: Mine Sight, by C. Ian White. The half-buried, gold-wrapped 55-gallon drums are a meditation on the waste our society generates, and a call to Techers to better the planet through their research and their personal lives. Administered by the Institute Art Committee and curated by Dustin Ericksen of Infrared Astronomy and Mike Rogers of Public Relations—both artists themselves—the site opened on October 23, 1999, with an exhibition called Metonym Ocean Size, by Jeremiah Day.

Who Says Columbus Was Right?

From the smallest variations in heat ever observed we move to the oldest—the cover story of the April 27 issue of *Nature* is the late-breaking news that a collaboration of 36 scientists from 16 institutions in four nations, with the U.S. contingent led by Professor of Physics Andrew Lange, has released the first detailed images of the infant universe at a mere 300,000 years old. These images are graven in the so-called cosmic microwave background (CMB), which permeates the universe in all directions and is the fossilized heat from the Big Bang. (Arno Penzias and Robert Wilson (PhD '62) discovered the CMB in 1965, earning them the Nobel Prize in physics in 1978.) Tiny, localized irregularities in the CMB's temperature bespeak subtle density fluctuations in the newborn universe—the seeds of the clusters of galaxies we see today—and their apparent size reveals the universe's shape and foretells its fate. Gross variations in the CMB were first seen in 1991 by NASA's Cosmic Background Explorer (COBE), which surveyed the entire sky but lacked the fine resolution to pick out these features.

Now the BOOMERANG (Balloon Observations of Millimetric Extragalactic Radiation and Geophysics) project has looked at roughly 2.5 percent of the sky with an angular resolution 35

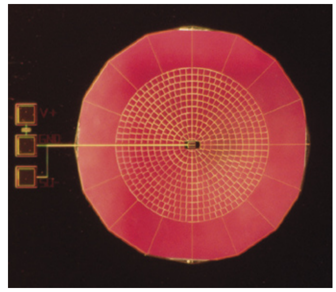


The BOOMERANG (bottom) and COBE data. For scale, the black circle at lower right is half a degree in diameter—the size of the full moon.

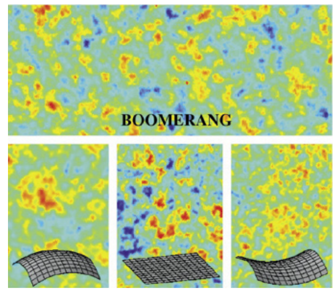
times that of COBE, detecting a complex pattern of temperature variations, typically of only 100 millionths of a degree (0.0001 kelvin). "The key to BOOMERANG's ability to obtain these images," explains Lange, "is the marriage of a powerful new detector technology developed at Caltech and the Jet Propulsion Lab with the superb microwave telescope and cryogenic systems developed in Italy." The two-ton telescope soared above 99 percent of Earth's atmosphere at an altitude of 37 kilometers on a NASA balloon that circumnavigated Antarctica in December 1998 and January 1999. BOOMERANG's $10\frac{1}{2}$-day flight ended within 50 kilometers of its launch site—not bad for an 8,000-kilometer throw!

(In a complementary effort, a Caltech team led by Professor of Astronomy Anthony Readhead is using a specially built radio telescope, the Cosmic Background Imager (CBI), to obtain CMB images at even sharper resolution. Together, BOOMERANG and CBI open an era of precision cosmological measurement that promises to provide new insights into fundamental physics.)

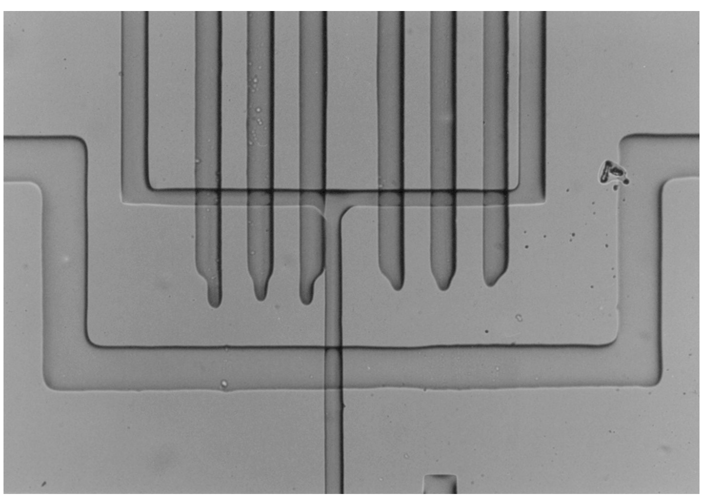
The first insight from BOOMERANG's data is that the universe is cosmologically flat, as explained at right. This agrees with a fundamental prediction of the "inflationary" model, a hitherto speculative, if widely accepted, scenario in which the universe violently and inexplicably grew from a subatomic volume to a respectable size just a split second after the Big Bang, stretching space flat in the process. So the flat-earthers have the last laugh: Columbus never sailed off the edge of the ocean, but Captain Picard may yet plunge off the edge of the universe. Except, of course, for the fact that the darn thing is infinite. □—*DS*



Left: BOOMERANG's button-sized heat-detecting elements, or bolometers, are freestanding spiderwebs micromachined out of silicon nitride and cooled to 0.3 kelvin—three-tenths of a degree above absolute zero. At that temperature, BOOMERANG can see the heat given off by a coffee maker on the moon, according to Jamie Bock. Bock, a research scientist at JPL and visiting associate in physics at Caltech, invented the detector technology and led the design and fabrication effort.



Above: The top panel shows a swath of BOOMERANG data 25 degrees wide. The bottom panels show the spot sizes predicted by different cosmologies. If space is an egglike closed curve (left), then parallel lines converge and the spots appear larger. If space is a saddle-shaped open curve (right), parallel lines diverge and the spots appear smaller. If space is flat (middle), the spots appear to be one degree in diameter.



This menorah-like object is actually a micromixer for fluids, cast from a single piece of soft rubber. The fluids flow from the top of the image to the bottom through the squared-off Y. The six "candles"—three on each arm—are the pressurizable channels that act as micropumps. The U-shaped channel across the stem of the candelabra is a pressurizable microvalve to control postmixing flow. The channels are about 50 microns wide.

RUBBER BABY MICRO PUMPERS

Caltech researchers have developed an itty-bitty pump about five times the size of a red blood cell. Silicon micropumps have been made before, but this one is made of soft, flexible material and opens up an entirely new approach to building nanoscale devices, according to Associate Professor of Applied Physics Stephen Quake and his colleagues, who report their findings in the April 7 issue of *Science*. Unlike the silicon-based micromachining techniques derived from the computer chip-making industry, this technique, called multilayer soft lithography, creates intricate castings in soft rubber. The work is an extension of soft lithography casting, originally developed by George Whitesides (PhD '64) at Harvard University.

"Basically, it's plumbing on a very small scale," says Quake. "We are trying to show that for certain applications it is useful to make microdevices out of soft rubber, rather than the hard materials like glass or silicon used in traditional micromachining. In order to make a valve, one needs to figure out how to make it seal, which is usually done with

Freshman Clinton Conley (far right) had the pleasure of riding the Edison International–JPL Year 2000 Rose Parade float. Conley was a senior on the Fullerton, California, Troy High School Science Bowl team, which won the JPL-sponsored Southern California regional contest in 1999 and then went on to place seventh in the nation. In addition to a JPL sweatshirt, T-shirt, cap, and lapel pin and a "priceless experience," Conley said he obviously gained some name recognition, because that autumn, when JPL was looking for a Caltech student to ride the float, his name came up. Because of the parade's early start time for the benefit of the East Coast TV audience and the pre-parade judging, participants have to get up just about the time when most undergrads are getting to bed—but for a once-in-a-lifetime experience, it was well worth it. "I thought that the whole thing was overwhelming. I needed a lot of coffee to wake up," he says. □—ME

a rubber washer. We made the entire valve out of the sealing material."

The pump works because of the material's softness and pliability. Embedded in a clear rubber chip the size of a postage stamp, the pump is actually a series of tiny, multilayer channels that each measure 50 by 30 by 10 microns, or millionths of a meter. (By contrast, a red blood cell is about 7.5 microns in diameter.) The pump operates in a manner similar to the peristaltic motions by which food travels through the intestines. By applying pressure in one of the channels, another channel above it or below it in the 3-D matrix can be closed off, thereby allowing the channel to act either as a pump or as a valve.

While this research is mainly aimed at demonstrating the feasibility of the technique, Quake says the pump could have a number of practical applications, including drug delivery. Doctors could one day implant a biocompatible pump and reservoir system into a patient's body to deliver drugs for such things as allergies, pain, diabetes, and cancer. The device could allow the drug to be delivered in a time-released manner customized for the patient, and could also contain an analytical component that would enable regular monitoring of the patient's condition.

Quake's own lab intends to use the microfabricated valves and pumps in two devices: a DNA sizer, which is a replacement for the current DNA sorting technique known as gel electrophoresis; and a cell sorter, a machine that physically separates microscopic materials such as bacteria or viruses. Both devices originated from research in Quake's lab.

Caltech has licensed this technology to Mycometrix Corporation of South San Francisco, which will apply it to develop a variety of commercial products.

In addition to Quake, the others involved in the research are Axel Scherer, Professor of Electrical Engineering, Applied Physics, and Physics; Marc Unger (PhD '99), a postdoctoral scholar in applied physics; Hou-Pu Chou (MS '96), a graduate student in electrical engineering; and Todd Thorsen, a graduate student in biochemistry. □—*RT*