precipitation eats away at the cloud layer yet relies on that same layer to sustain itself. Aerosol particles mediate the precipitation–cloud interactions: The higher the aerosol concentration, the more numerous the water droplets and the longer it takes for the droplets to grow large enough to coalesce into rain. To put it in predator–prey vernacular, the hunt becomes more challenging.

Building on those basic concepts, the researchers distilled the cloud-aerosol-precipitation system into a system of three equations. Although the equations differ from Lotka and Volterra's predator–prey model, the solutions exhibit similarly rich dynamics.

The model predicts that aerosol-rich skies should eventually settle into a steady state like that shown in figure 2a, with a light drizzle of rain offsetting the formation of new cloud droplets. Aerosol-deficient clouds, on the other hand, are likely to precipitate faster than they can replenish themselves and collapse into a downpour of rain.

The team's model also suggests the possibility of limit cycles like the one shown in figure 2b, with periods of gradual cloud growth punctuated by brief bouts of heavy rain. But whereas the steady state and unstable collapse have been documented in field observations, evidence in support of limit cycles—outside of LES results and anecdotal data—remains scarce. "We hope to strengthen that aspect of the study with observations," says Feingold, "but the measurements aren't easy."

Still, Feingold sees the pared-down model as a potentially valuable complement to LES-type approaches: "We don't want to discard all of the details. But to the extent that we can, we think it's also worth trying to use simple models to see the bigger picture."

Ashley G. Smart

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Entanglement gets scaled up in an optical frequency comb

Using a single nonlinear optical element, researchers have entangled dozens of the comb's optical modes.

The appeal of quantum computing is that by making use of quantum systems in highly entangled states, one can feasibly solve problems (such as factorizing large integers) that would take far too long on even the most powerful of classical computers. Still, useful quantum computation would require a register of some hundreds or thousands of quantum entities, such as two-level qubits or continuously valued qumodes. Scalability in the control over quantum information is thus an important research goal.

Toward that end, Olivier Pfister and colleagues at the University of Virginia have shown that in a single step, they can simultaneously manipulate at least 60 qumodes, entangling them in sets of four.[1] Their experiment is a step toward implementation of a scheme called one-way quantum computing.

One way or the highway

The most familiar approach to quantum computing is much like classical computing: Start with a blank slate of unentangled qubits, manipulate them in a controlled way that depends on the problem to be solved, and make measurements to read out the answer at the end.

A one-way quantum computer, in contrast, starts with the qubits already in a particular highly entangled state called a cluster state.[2] The computation is then performed by making a series of single-qubit measurements. The

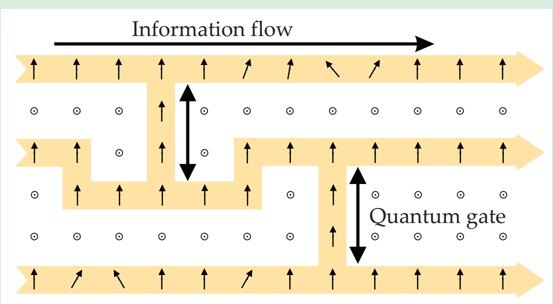

Figure 1. One-way quantum computation. Starting with an array of qubits in a highly entangled state—each site on the square lattice hosts a qubit, and each pair of nearest neighbors is directly entangled—a computation is carried out solely through single-qubit measurements, indicated by the directions of the black arrows. (Adapted from ref. 2.)

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advantage is that the hardest part—constructing the entangled state—is all done in advance and is the same for every computation. The single-qubit measurements are comparatively easy.

Basic elements of the scheme are illustrated in figure 1. The cluster state is a square lattice of qubits in which each nearest-neighbor pair is directly entangled. The qubits are measured sequentially, from left to right, in the directions shown by the black arrows. (The ⊙ symbols are arrows pointing out of the plane of the page.) A chain of in-plane measurements serves to either propagate the state of a qubit (vertical arrows) or rotate it (tilted arrows) along the chain. The conjunction of two chains forms a simple quantum gate, which can be combined to construct the quantum analogues of classical logic gates. The out-of-plane measurements serve to clean up the extraneous sites and keep the information chains separate.

One can also design a scheme for a one-way quantum computer based not on qubits but on continuously valued qumodes, such as squeezed optical modes.[3] A coherent light beam has an inherent quantum uncertainty in its electric field; in a squeezed optical state, the uncertainty in one part of the wave cycle is reduced at the expense of another. Two optical beams are entangled if their correlations—uncertainty in their sum or difference, for example—display the characteristics of a squeezed state.

To create entangled states of light, researchers typically use an optical parametric oscillator (OPO), a combination of an optical cavity and nonlinear crystals that split input photons into pairs of lower-energy output photons, subject to conservation of energy and momentum. The quantum fluctuations of the input, or pump, mode are transferred onto both of the output modes, which are thereby entangled.

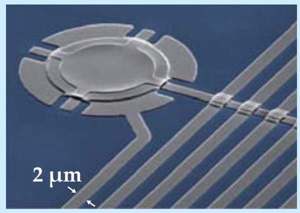
Most efforts to entangle optical modes into a cluster state suitable for quantum computing involve building up the state bit by bit. Making a larger cluster state thus requires more hardware and effort. But, as Pfister and theorists Steven Flammia and Nicolas Menicucci determined, the equipment and effort might be greatly reduced by

physics update

These items, with supplementary material, first appeared at http://www.physicstoday.org.

A sound strategy for pollination. Plants gain an advantage in attracting pollinators if they stand out from the crowd. And so, many plants have evolved flowers with spectacular coloration or enticing scents. Ralph Simon (University of Ulm) and colleagues now report that the Cuban vine *Marcgravia evenia* uses a novel trick—based on acoustics rather than visual or olfactory effects—to attract its pollinating bats. Just above its purple flowers, *M. evenia* presents specialized concave leaves, shown here, to the foraging bat. The leaf's spherical-cap geometry enables it to return a strong and consistent echolocation reflection over a wide angular range. Thus, as the bat flies around in the vicinity, the plant's steady signal is prominent amongst the random din of echoes from surrounding foliage. To check the effectiveness of the specialized leaf, Simon and colleagues hid a sugar-water feeder in artificial foliage and, in various trials, accompanied it with a replica of *M. evenia*'s concave leaf, a replica of the vine's nonspecialized leaf, or nothing at all. Bats consistently found the feeder more quickly when the concave leaf was present. It's hard to imagine, write the authors, that the specialized leaves can have any evolutionary advantage other than attracting pollinators. (R. Simon et al., *Science* **333**, 631, 2011; image courtesy of Corinna U. Koch.) —SKB

Sidebands get to the mechanical quantum ground state. Last year researchers at the University of California, Santa Barbara, demonstrated quantum effects in the motion of a macroscopic object. They achieved control of phonon energy states in a high-frequency (6-GHz) micromechanical oscillator after cryogenically cooling it to its ground state. Now, researchers at NIST, JILA, and the University of Colorado at Boulder have employed photon–phonon coupling to reduce the vibrational energy of a low-frequency (10-MHz) micromechanical oscillator to the ground state. Their setup consisted of a flexible 15-μm-diameter aluminum membrane (the gray disk in the image) coupled to a superconducting microwave resonant circuit. After cooling their system to 15 mK, the researchers applied a microwave field at a frequency just below resonance, generating so-called sideband photons that effectively steal energy from the membrane's phonons. For applied photon numbers on the order of 10^4, the oscillator's motion enters the quantum regime, possessing on average less than one phonon. The researchers also detected the oscillator's displacement with a precision that comes closest to date to the theoretical Heisenberg limit. The low-frequency system's relatively longer phonon lifetimes and larger displacements could pave the way to storage of quantum information and generation of entangled states in mechanical systems. (J. D. Teufel et al., *Nature* **475**, 359, 2011.) —JNAM



The chaotic orbits of asteroids and Earth. Ever since Isaac Newton, astronomers and mathematicians have sought to understand the dynamics of the solar system, but even the seemingly simple case of the three-body Sun-Earth-Moon system eludes an analytical solution (see PHYSICS TODAY, January 2010, page 27). Obtaining accurate results for Earth's motion requires numerical calculations that include not only the Sun, Moon, and other planets but also the larger asteroids such as Ceres (now considered a dwarf planet), whose mass is 1/6000 of Earth's, and Vesta, less massive still by a factor of 4. Long-term knowledge of Earth's position is useful for paleoclimate studies, since the changes in incident sunlight allow calibration of geological records (see PHYSICS TODAY, December 2002, page 32). In 2004 Jacques Laskar and colleagues at the Paris Observatory calculated Earth's position back 40 million years, allowing calibration of the Neogene period, which began 23 Myr ago. But Earth's orbit is chaotic, with uncertainties increasing by an order of magnitude every 10 Myr, and it was not known how far the numerical solutions could be extended and still be valid. Laskar and coworkers have now established that the limit is 60 Myr. The researchers found that the motions of the five large asteroids they included were much more chaotic than previously thought. Furthermore, the effects of close encounters between asteroids—particularly Ceres and Vesta—on planetary motion are the limiting factor for establishing a longer-term history of Earth's orbit. (J. Laskar et al., *Astron. Astrophys.* **532**, L4, 2011.) —RJF using an optical frequency comb—the equally spaced modes of an optical cavity—as the qumodes.[4] A suitably designed OPO could entangle many pairs of modes with a single pump mode, because there are many pairs of modes whose frequencies sum to the pump frequency. The researchers developed a scheme whereby a single OPO and a pump spectrum of 15 frequencies suffice to create the topological equivalent of an arbitrarily large cluster state. Pfister and his experimentalist colleagues have now taken the first step toward implementing the scheme in the lab.

Entangling qumodes

Flammia, Menicucci, and Pfister found that to create a cluster state with the

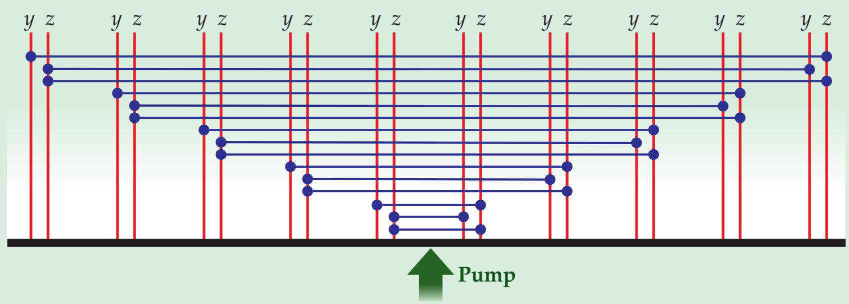
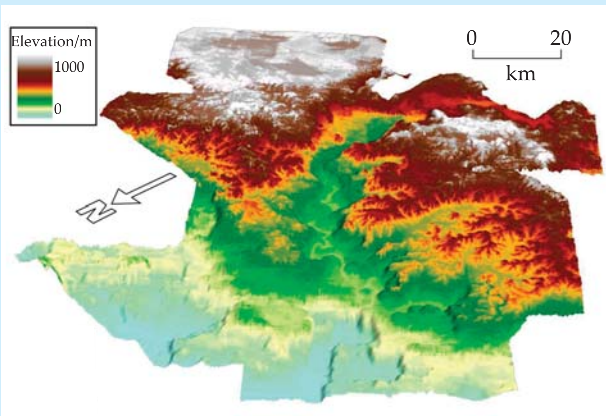


Figure 2. Entangling many modes (red lines) in an optical frequency comb with a single pump mode. The green arrow represents half the pump frequency; an optical parametric oscillator generates entanglements, represented by the blue lines, between modes whose frequencies add up to the pump frequency. Because the *y* and *z* polarizations of each frequency are treated as separate quantum modes, the modes are entangled in groups of four.

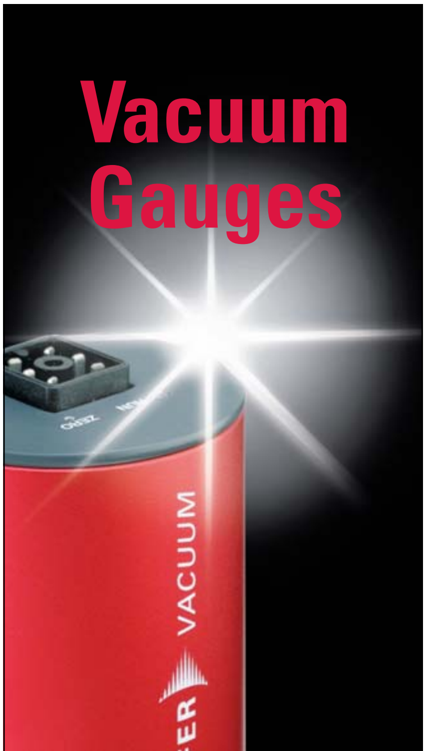
An ancient buried landscape. The mountainous river-cut topography in the figure resembles that of the Ozark Plateau in the southwestern US. In fact, as Ross Hartley of Cambridge University and his colleagues have discovered, the craggy landscape lies off Scotland's northern coast, buried beneath both the Atlantic Ocean and 2 km of rock. Hartley and his colleagues found the river-cut landscape in a three-dimensional seismic survey of Europe's continental shelf. Being made of sedimentary rock, the landscape must have formed under water, but it was evidently once above sea level and exposed to the elements long enough for water to erode a network of valleys. How did the uplift take place? Water carves valley networks in more or less predictable patterns. When Hartley and his colleagues modeled the landscape's erosion history, they found a surprise: The patterns could be explained only if the uplift took place over a total of 1 million years in three discrete steps, each about 200–400 m



high. The uplift is consistent with the action of the putative Icelandic plume, a convective upwelling of hot material that extends from the lower mantle. When the plume reaches Earth's crust, it spreads radially beneath the crust, exerting upward pressure. An unusually strong upwelling event could have lifted the now-buried landscape temporarily above sea level. (R. A. Hartley et al., *Nat. Geosci.* **4**, 562, 2011.) —CD

Soda cans focus sound to subwavelength spots. Beating the diffraction limit requires accessing a field's evanescent waves, which harbor its subwavelength spatial details but don't propagate—they are stuck to the field's source. The scanning probe of a near-field microscope can directly access those evanescent waves (see PHYSICS TODAY, July 2011, page 47). But it's also possible to directly convert the standing waves to propagating ones by scattering them with a metalens—a cluster of strongly coupled subwavelength resonators—an approach introduced last year by ESPCI ParisTech researchers led by Geoffroy Lerosey. The Paris group has now demonstrated that broadband, audible sounds can be manipulated and focused onto spots as small as 1/25th of their wavelength λ. In a refreshingly low-tech experiment, various tones near 400 Hz from eight loudspeakers surrounding an array of empty soda cans were used to excite resonant modes with spatial variations as small as the diameter of a can. Using the principle of time reversal (see PHYSICS TODAY, March 1997, page 34), the researchers then focused the modes by adding them coherently at a specific time and location and incoherently at other times and positions. Microphone-recorded maps of the acoustic pressure upon time reversal before and after cans are introduced demonstrate the subwavelength focusing. (Videos also show the dynamic acoustic intensity as the modes are focused.) The authors say the approach may lead to exotic new designs of smart sensors and actuators. (F. Lemoult, M. Fink, G. Lerosey, *Phys. Rev. Lett.* **107**, 064301, 2011.) —RMW

Acoustic levitation. A popular 1980s television commercial featured a man being blown backward by the sound coming from his stereo. Though a speaker's pressure field isn't nearly that strong, acoustic pressure can suspend millimeter-sized objects against the force of gravity. New work by Pierre Lambert and colleagues at Belgium's Université libre de Bruxelles compares existing theoretical models, numerically computes the strength and direction of the acoustic forces, and validates those results with experimental measurements on objects suspended in standing waves. The researchers find that for spherical objects with radii bigger than one-sixth of the acoustic wavelength—or for nonspherical objects—analytical models don't suffice and numerical modeling is required. The team's calculations and experiments show that at pressure nodes, levitation in an axially symmetric standing wave is stable for both small displacements and angular tilt. Furthermore, when an instrument such as tweezers is inserted laterally into the field, the pressure distortions will push the levitated object to the probe, turning the levitator into a component feeder. Levitation could also find use in a wide variety of other settings; isolated analysis of small samples of proteins and the sorting and separating of items according to their size are just a few examples. (V. Vandaele, A. Delchambre, P. Lambert, *J. Appl. Phys.* **109**, 124901, 2011.) —RJF



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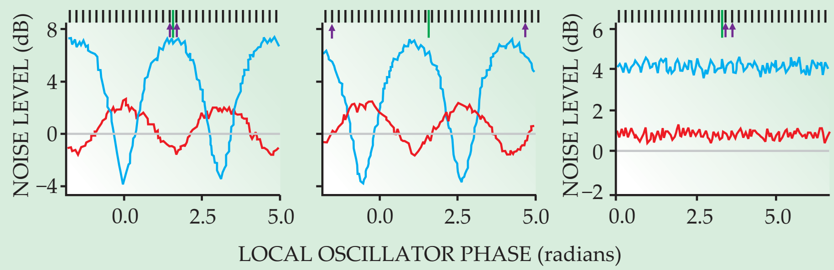

Figure 3. Checking entanglement of a four-mode cluster comprising two frequencies. In each panel, the frequencies being checked are represented by the purple arrows, the black tick marks are the modes of the optical frequency comb, and the green line represents half the pump frequency. The red and blue data curves are the noise levels of two different linear combinations of the four modes. Noise levels of less than 0 dB constitute entanglement. The left and center panels are checks of modes whose frequencies sum to the pump frequency; they're expected to be entangled, and they are. The rightmost panel is a check of modes that are not expected to be entangled, and they are not. (Adapted from ref. 1.)

desired topology it is necessary to use the *y* and *z* polarizations of a single frequency as separate qumodes. To address both polarizations, and to create entangling interactions between modes of different polarization, the OPO must be highly exotic, consisting of two distinct nonlinear crystals, one rotated with respect to the other.

Getting the alignment of the crystals just right, and controlling the relative strengths of their nonlinear processes, was an experimental challenge, but Pfister and colleagues have now achieved their first success by entangling modes in groups of four. As shown in figure 2, that could be accomplished with a single pump frequency, since each cluster of four entangled modes comprises just two frequencies.

To test the entanglement, the researchers measured the noise level in the electric field as a function of phase for linear combinations of the entangled modes. To make the phase-specific measurements, they combined the frequency comb modes with a two-color local oscillator, a beam whose spectrum contained the two frequencies whose entanglement they wanted to check. They ran the check on 15 clusters of modes that they expected to have entangled, starting with the adjacent modes in the frequency comb, as shown in the left panel of figure 3, and ending with the widely spaced pair shown in the center panel. A noise level of 0 dB is the minimum level of quantum fluctuations of modes that are unsqueezed and unentangled; noise levels below 0 dB constitute entanglement.

All the clusters the researchers checked were entangled, and to an almost identical degree. They could check only 15 clusters because of technical limitations in the local-oscillator frequencies they could produce; it's likely that they actually entangled at least 45 four-mode clusters, and possibly as many as 150.

Equally important to the eventual formation of a large cluster state is to ensure that there is no entanglement between modes that shouldn't be entangled. And indeed, that is what the researchers found, as shown in the rightmost panel of figure 3.

Connecting the four-qumode clusters into larger cluster states is mostly just a matter of adding more frequencies to the pump spectrum. But before the optical cluster state can be used for quantum computation, an additional challenge must be overcome. Simple electric-field measurements, as with the local oscillator, don't work as the single-qumode measurements in a one-way quantum computing scheme. Instead, it's necessary to count the mode's photons with 100% efficiency. "Such measurements were unthinkable just a few years ago," Pfister says, "but Sae Woo Nam's group at NIST has made giant strides in that respect, and photon-number-resolving detection has now come of age."

Johanna Miller

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