TODAY, July 1995, page 22), the phase between the pressure and velocity is very close to 90°. Consequently, such an engine must rely on an irreversible process for transferring heat to the gas and converting it into work, which limits the engine's efficiency: Current standing-wave thermoacoustic engines typically achieve no better than about 20% of the maximum Carnot efficiency.

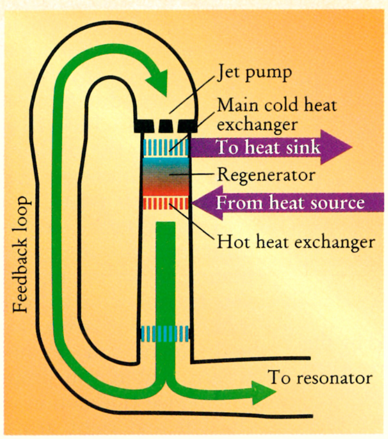
Traveling acoustic waves, in contrast, have their pressure and velocity in phase with each other. Peter Ceperley of George Mason University noted 20 years ago that when traveling waves pass through a regenerator, the thermodynamic cycle of compression, heating, expansion, and cooling that the gas undergoes is the same as in a Stirling engine, where mechanical pistons establish the proper phasing of the gas motion.[2] With the gas velocity and pressure in phase, a traveling-wave acoustic engine can use a reversible, much more efficient heat transfer process. It therefore does not suffer from the inherent efficiency limitations of standing-wave engines.

Viscous dissipation and other losses have plagued the experimental implementation of traveling wave engines, and the high expectations for these engines are only now beginning to be realized. Just last year, a team led by Taichi Yazaki of the Aichi University of Education in Aichi, Japan, first demonstrated that such an engine can be self-sustaining.[3] Now Backhaus and Swift have gone the next step, showing that traveling-wave acoustic engines can have high efficiencies.

Engine design

Five meters long and welded together from steel pipe, the Los Alamos engine consists of a looped tube attached to the small end of a baseball-bat-shaped acoustic resonator. The loop, illustrated in the accompanying figure, contains the heart of the engine. Within the loop, the regenerator—which looks like a tightly packed cylindrical pile of window screen mesh—has its upper end kept at ambient temperature by a water-cooled heat exchanger; heat applied to the lower end provides the energy for the engine. The resonator establishes the operating frequency of 80 Hz.

The loop itself acts like the feedback network in an electronic amplifier circuit, explains Backhaus. "By configuring the acoustic impedances in the loop for positive feedback with the proper traveling-wave phasing at the regenerator, the engine becomes an amplifier for traveling waves." When the apparatus is filled with 30 atmospheres of helium and heat is applied, traveling acoustic waves are generated with peak-to-peak amplitudes of up to 6 atm.



A THERMOACOUSTIC STIRLING ENGINE developed at Los Alamos uses heat to amplify traveling acoustic waves. Sandwiched between cold and hot heat exchangers, a regenerator transfers energy to sound waves as they propagate through the engine's helium gas. Part of the acoustic power produced in the regenerator is fed back around the closed loop; the rest goes to a resonator where it can be tapped to perform work. The jet pump eliminates any net mass circulation around the loop. (Adapted from ref. 1.)

The prototype engine transformed up to 30% of the input heat into acoustic power delivered to the resonator—up to 700 W. This efficiency, which corresponds to over 40% of the Carnot efficiency, already rivals internal combustion engines, and further increases are in store.

Reducing losses

The researchers incorporated several key improvements into their engine to achieve their efficiency results. The first step was to keep the feedback loop containing the regenerator much shorter than one-quarter of an acoustic wavelength. Making the loop short decreases the surface area, thereby reducing the losses around the loop due to viscous drag and thermal hysteresis at the walls.

Furthermore, with a short feedback loop, the acoustic impedance that the traveling wave experiences is dominated by the loop instead of the regenerator. Backhaus and Swift were therefore able to control the impedance, allowing them to maintain the desired phase relationship between the pressure and velocity as well as to get high pressure oscillations while keeping the velocity amplitude small, which further reduced viscous losses.

An unanticipated problem was that there was a large nonzero average mass flow circulating around the loop, which had a dramatic effect on their engine's performance: It produced an additional heat load that cut the engine's efficiency nearly in half. To eliminate the unwanted mass flux, Backhaus and Swift devised a special jet pump for the feedback loop. The strategically shaped pump creates a much larger pressure drop for one direction of motion in the oscillating gas than for the other—"like a rather leaky diode," describes Swift—and this asymmetry can be adjusted to cancel the streaming mass flow.

The output of a traveling-wave thermoacoustic engine can be tapped with an electroacoustic or other transducer. Alternatively, the engine can be used to drive an acoustic load such as a thermoacoustic refrigerator. This combination may prove quite appealing, providing refrigeration with no sliding seals, moving parts, or chlorofluorocarbons or other potentially dangerous refrigerants. "Thermoacoustic engines and refrigerators have been attractive in niche applications," comments Steven Garrett, an acoustician at Pennsylvania State University. "Now they may become even more efficient than internal combustion engines and vapor compression refrigerators."

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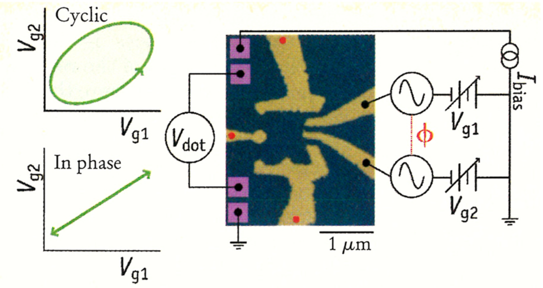
Adiabatic Quantum Electron Pump Produces DC Current

> You can control the flow of electrons in a quantum dot by cyclic changes in the wavefunction.

If you know what you're doing and have suitable equipment, you can make a quantum dot, a tiny conducting region that contains anywhere from a handful to several thousand electrons. A number of experimenters have studied the electron transport properties of such dots. Now a group at Stanford University and the University of California, Santa Barbara, has made an open quantum dot, changed the shape of the system cyclically, and found that a finite current flows. This surprising effect requires quantum phase coher-



ADIABATIC QUANTUM ELECTRON PUMP. In the micrograph, quantum dot is in open space formed by the five (yellow) metal gates. Red spots mark the three gates that control the size of the conductance. Quantum dot shape is changed by applying sinusoidal voltages with an adjustable phase difference on the other two gates. In plots at left, bottom one shows applied voltages moving in phase, and the top one, moving out of phase. Light blue area is proportional to amount of current transferred. (Figure adapted from ref. 1, courtesy of C. Marcus, Stanford.)

ence and is observable only at a temperature low enough to preserve quantum phase. The effect was recently reported[1] by Michael Switkes and Charles Marcus (Stanford), and Kenneth Campman and Arthur Gossard (UCSB).

Experiment

The experimenters use a two-dimensional electron gas with metal gates placed on top of the sample to confine the electrons. To form an open quantum dot, the team electrostatically depletes the sample in the space between two skinny, conducting leads, which are part of the original two-dimensional electron gas and are well connected to a reservoir of electrons. (See the figure on this page.) In the micrograph, the light areas are the gates. The three red spots mark the three gates that control the size and thereby the conductance of the point-contact leads. The experimenters adjusted the voltages on these gates to transmit about two transverse modes of the electron waves—that is, one wavelength wide—giving an average conductance through the dot of order $2e^2/h$, or roughly $(13\ k\Omega)^{-1}$.

By applying sinusoidal voltages with an adjustable phase difference ϕ on the remaining two gates (at the right), the team can change the boundary of the dot, and thus the shape of the dot. Says Marcus, "Those two gates move the edge of the puddle of electrons. We use 1–20 MHz, very slow compared to the relaxation time of the electrons; that is, we change the shape adiabatically." Because the electron wavefunction extends into the leads, these adiabatic changes can transport charge to or from the reservoirs, through the openings between the left-hand gates. "If the periodic deformation depends only on a single parameter, you can't get net transport—any charge that flows during the first half period will flow back during the second," the experimenters explain in their paper.

This process can be compared to the cyclic motion of swimming. If you try to swim by just moving your arms up and down, you go nowhere. But if you properly phase the motion of the left and right arms, you can move forward. In the figure, the bottom left-hand graph shows the applied voltages V_{g1} and V_{g2} oscillating in phase, and the path in the space of these voltages is a straight line. In the top left-hand graph, the two voltages move out of phase, and the path (shown in green) is elliptical. According to theory, the light blue area is proportional to the amount of current pumped.

For technical reasons, instead of measuring short-circuit current, the Stanford–UCSB team measured open-circuit voltage. The team made measurements over a range of magnetic field from 30 to 80 millitesla, thus allowing several quanta of magnetic flux to penetrate the dot. The quantum pumping has a sinusoidal dependence on the phase difference between the two shape-distorting AC voltages applied to the gates. The experimenters found random fluctuations of amplitude. As they raised the temperature from about 1/3 K to 5 K, quantum coherence disappeared, and the current flow was reduced by a factor of almost 100.

One way of thinking about the pumping process, says theorist Ned Wingreen (NEC Research Institute in Princeton, New Jersey), is to visualize a magnetic field perpendicular to the plane of a loop. "A charged particle moving once around the loop picks up a certain extra phase because of the field. That's the Aharonov–Bohm effect." Similarly, says Wingreen, "in the Stanford–UCSB system, when one cyclical trajectory of the voltage is traversed, you have moved some definite amount of electron charge. To a first approximation, it doesn't matter how fast or slowly the cycle is completed."

Even in the absence of quantum coherence, one can pump charge by periodically modulating the conductances of the leads, thus taking advantage of the so-called Coulomb blockade effect. These latter experiments can produce a current of precisely one charge per cycle. (Such experiments are being investigated as possible standards of electrical current.) By applying two AC control voltages with different phases to an isolated dot, electrons can be coaxed through the dot one at a time. The number of electrons per cycle and direction of the pumping are determined by these voltages. There are negligible random fluctuations due to quantum effects. By contrast, in the new experiment, the pumping isn't driven by cyclic changes to barriers. Instead, it's the shape changes in the confining potential that affect the interference pattern of the coherent electrons in the device, causing a net current to be pumped. Because the interference patterns are random, the direction of current flow is random and is, for instance, sensitive to small changes in applied magnetic field, providing evidence of the quantum nature of this effect, says Marcus.

Theory

If you try to determine the quantum mechanical wavefunction for a given problem, there is no one unique solution, because you can give the wavefunction a different phase. In the Stanford–UCSB experiment, you start with a given set of voltages on the gates and pick a particular phase convention, so you know the definite electron wavefunction you start with. Now you go through the adiabatic pumping process, applying sinusoidal voltages to the gates. The wavefunction will change under the external voltages. However, after a cycle of the pumping voltages is complete, you'll return to the same configuration of voltages you started with—but the wavefunction may have its phase changed from the initial wavefunction. This is the so-called geometric, or Berry, phase (after Michael Berry of Bristol University). The fact that a net current flows in a particular direction is intimately related to the fact that the electronic state after one cycle is not identical to the initial state, but is different by a phase factor.

For a well isolated quantum system, the idea of the geometric phase can be well formulated, but for systems connected to reservoirs, the idea of the geometric phase is trickier. Sixteen years ago, in connection with his work on the quantum Hall effect, David Thouless (University of Washington) developed a theory of adiabatic electron pumping. Under certain conditions, electrons subjected to a periodic potential would adiabatically follow the translations of the potential. Thus the charge transferred would be quantized when the potential was translated by one period. Recently, Boris Spivak (University of Washington), Fei

Zhou (NEC Research Institute) and Boris Altshuler (Princeton University)—as well as Piet Brouwer (now at Harvard University)—have found that in a mesoscopic system, pumping becomes a random effect.

Very recently, Altshuler and Leonid Glazman (University of Minnesota) have pointed out that the motion of the potential considered by Thouless may be viewed as a linear superposition of two standing waves. The time dependence of the amplitudes of these waves, $V_{g1}(t)$ and $V_{g2}(t)$, differ by some phase. Spatial translation by one period corresponds to one cycle of motion along some closed contour in the parameter space $\{V_{g1}, V_{g2}\}$. The pumped charge is nonzero only if the area enclosed by this contour is nonzero (so there is an appropriate phase shift between the standing waves, as in the phased motion of a swimmer's arms).[2] Altshuler and Glazman say that this visualization allows one to cast the pumping process in more general terms, good for open mesoscopic systems, such as quantum dots. If you slowly vary the shape of the quantum dot so that the area discussed above is nonzero, Glazman explains, then the transmission amplitude acquires some additional phase (the Berry phase) by the end of each cycle. That's equivalent to some charge passing through the dot. Furthermore, one can construct some quantity related to the transmission amplitude that's analogous to a magnetic field. Then the pumped charge can be expressed as the flux of this "magnetic field" through the contour, analogous to the Aharonov–Bohm effect.

What next?

Glazman notes that in most applications of chaos ideas to quantum dots, workers haven't worried about electrons interacting with each other. Now he'd like to see measurements involving a partially closed dot, which would force the electrons to spend more time interacting with each other. Wingreen suggests, "Maybe one can study the decoherence of the electrons in the quantum dot using a Berry phase geometry in the same way as Moty Heiblum [Weizmann Institute of Science] and his collaborators studied the decoherence of electrons in the quantum dot using an Aharonov–Bohm geometry [see PHYSICS TODAY, January 1997, page 19]."

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Experiments at Jefferson Lab and MIT Probe for Strange Quarks in the Proton

> If you can measure a parts-per-million parity violation in the elastic scattering of electrons off protons with enough precision, you get to look at the strangeness structure of the proton. These demanding experiments are under way at accelerators old and new.

The simplest description of the proton in terms of constituents regards it as a bound state of the three "valence" quarks that account for its quantum numbers: two up quarks, each with charge $+\frac{2}{3}e$, and one down quark, with charge $-\frac{1}{3}e$. But we know that's too naive. Experiments over many years have shown that quarks carry only about half the proton's linear momentum and a quarter of its angular momentum.

The latter observation has become known as the proton's "spin crisis." (See the article by Robert Jaffe in PHYSICS TODAY, September 1995, page 24.) Since the mid-1980s, deep-inelastic scattering experiments at CERN and the Stanford Linear Accelerator Center have been unveiling a surprising picture of the proton: The three valence quark spins carry something like 60% of the proton's spin, but roughly half of that valence contribution is canceled by the spins of nonvalence quarks and antiquarks from the proton's low-momentum "sea" of quark–antiquark pairs. One would not have expected that most of the proton's spin is due to things other than quark spins—perhaps gluons or the orbital motion of quarks.

In relativistic quantum theory, a sea of evanescent quark–antiquark pairs must be present at some level, but the great surprise was that these sea quarks should be so strongly polarized in the direction opposite to the proton's spin. (Quarks, like protons and electrons, are spin-½ fermions). If one then invokes apparently sound arguments about the approximate SU(3) symmetry of the three light-quark flavors, one concludes that the strange (and antistrange) sea quarks contribute about one-third of the antipolarized countercontribution—that is to say, *minus* 10–15% of the proton's spin.

So significant a role for strange quarks in the proton, whose net strangeness is of course zero, would be at once perplexing and plausible. It's perplexing in view of the *ad hoc* "Zweig rule," which summarizes the general observation that the contribution of nonvalence quark pairs to hadronic scattering processes is strongly suppressed. And yet it's also plausible, because the strange quark (s) is light enough for virtual $s\bar{s}$ pairs to bubble continually out of the sea. The three "heavy quarks" (charmed, bottom, and top) are much too massive to make significant appearances. Because the strange quarks are the only nonvalence light quarks in the proton, they provide a unique window on the physics of the sea.

The so-called naive quark model, despite its many successes, has long been superseded by quantum chromodynamics (QCD), the full-blown gauge field theory of the strongly interacting particles, their quarks, and the gluons that bind them. But the theory is so mathematically difficult that one cannot understand the structure and interactions of the proton without the aid of phenomenological models. The strength of the couplings and the fact that gluons, unlike photons, feel the force they are transmitting, make it very hard to deduce ground-state properties of the hadrons from first QCD principles.

New elastic scattering experiments

To investigate further the intriguing evidence of strange-quark contributions to the proton (and neutron) from the deep-inelastic scattering experiments, the venerable Bates Linear Accelerator Center at MIT and the new Thomas Jefferson National Accelerator Laboratory in Newport News, Virginia, have undertaken exacting experiments to measure the tiny parity-violating asymmetry one expects to see in the elastic scattering of longitudinally polarized electrons off unpolarized protons at energies of a few GeV. (The deep-inelastic experiments, which examine the high-momentum-transfer inelastic scattering of electrons, muons, and neutrinos off protons and neutrons, provided the principal dynamical evidence for quarks in the nucleons in the early 1970s.)

The electromagnetic interaction,