a cell of linear dimension up to 100 Å. (By contrast, the simulations reported by the IBM Kingston group had used up to 2×10^5 molecules.) The equations of motion were integrated for intervals of up to 10^{-9} seconds using a time step of about 10^{-14} sec. Each bin contained about 10 molecules and the averaging procedure used up to 5000 steps. If the bin size for averaging had been too large, there would not have been enough fluid velocity vectors to reveal the spatial patterns in the flow; if too many time steps had been used for averaging, the dynamical features of the flows would have been lost. On the other hand, small bins and too few time steps in the averaging would not have revealed smooth and steady hydrodynamic flows but would have shown the disorder characteristic of molecular motion. The success of the Schlumberger simulation therefore rested on the judicious choice of the bin size and the time steps in the averaging procedure.

Poiseuille flow

When a viscous and incompressible fluid is forced to flow between two walls, by the application of pressure at one end, for example, not all points on the fluid front move with the same velocity. The tangential component of the fluid velocity is a quadratic function of the distance from the walls, vanishing at the walls and having its maximum value in the middle. This parabolic velocity profile defines a flow pattern called Poiseuille flow, which has been well characterized by analytical studies of the equations of hydrodynamics. But one must impose the no-slip boundary condition on the hydrodynamic equations to obtain analytical solutions corresponding to Poiseuille flow.

In the simulation that the Schlumberger group reports, Poiseuille flow emerges quite naturally when molecules are subjected to a uniform external force in a direction parallel to the walls. Poiseuille flow has been seen earlier in numerical simulations: The IBM Kingston group studied it in molecular dynamics simulations using walls that had physical properties similar to those assumed by Maxwell in his theoretical model, and Kadanoff, Guy McNamara and Gianluigi Zanetti obtained the flow pattern using cellular automata.[4] But confirmation of this well-characterized fluid flow in the Schlumberger simulation showed, first, that simulations of a few thousand molecules using the molecular dynamics technique may be usefully employed to study hydrodynamics and, second, that the no-slip boundary condition is a natural outcome of the interaction between the molecules of the solid and the fluid. Furthermore the simulation showed that the mean fluid flow imposes a uniform drift on the molecular Brownian motion and that attraction between molecules in the walls and those in the fluid localizes the fluid molecules near the walls only temporarily.

Moving contact lines

To study the flow of two immiscible fluids and the dynamics of the meniscus separating them, the Schlumberger group modified the potential between molecules of different species. The interaction between the molecules of the same species was of the standard Lennard-Jones form, but the attractive part (r^{-6}, where r is the intermolecular distance) of the potential between different species was reduced. In the simulations for the velocity field shown in the figure on page 17, the attractive interaction between the two liquids was completely removed, while those between each of the two liquids and the walls were reduced by different amounts. The latter choice led to preferential wetting.

Molecular dynamics simulation of the two-fluid system showed that the contact angle the meniscus makes with the walls changes slowly with time. The fluid that preferentially wets the walls forms a thin film along the walls when it moves or is displaced by the other fluid. Most important, the simulations show that the no-slip condition breaks down at the contact line and that a jet flows back into the fluid (see the figures on pages 17 and 18).

The behavior seen in the simulations is consistent with observations made by Elizabeth B. Dussan V. (now at Schlumberger-Doll Research) in 1977. Dussan used a dye to study qualitatively the motion of the interface between oil and glycerin in a vertical Plexiglas tube when the glycerin was pumped up so that it displaced the oil. "It would be very nice if the simulations could be extended to give a more quantitative handle on the contact angle," Dussan told us. "The angle changes rapidly near the boundary, but it is difficult to determine precisely the shape of the meniscus a few microns away from the boundary." The simulations might also help map out the viscous drag and thereby provide useful insights into the singularities obtained in earlier theoretical treatments of fluid flows near the contact line.

—Anil Khurana

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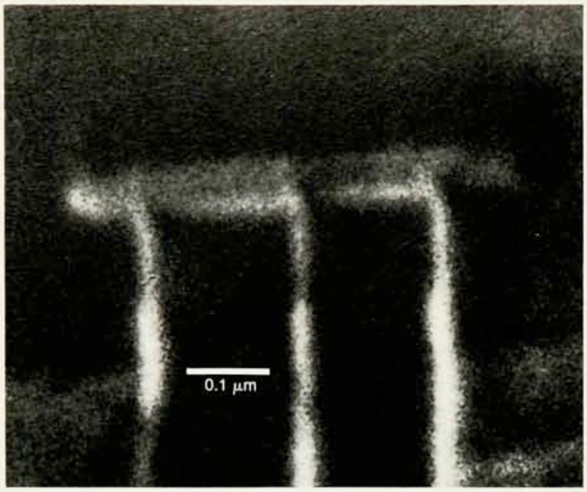
VERY SMALL TUNNEL JUNCTIONS SENSE THE EFFECT OF SINGLE ELECTRONS

In most capacitors the gain or loss of a single electron is hardly noticed. But in the very small tunnel junctions that can now be made, the capacitance is so small—on the order of 10^{-16} farads or less—that the addition of just one electron can change the electric potential across the barrier by several millivolts. In that case, a single electron certainly can make a difference. The change in potential when an electron tunnels across the junction is enough to impede the tunneling of the next electron. The resulting block of current flow—called the Coulomb blockade—should show up in the current-voltage characteristics of small-capacitance tunnel junctions at low temperatures.

Ivar Giaever (General Electric) and Hans-Rudi Zeller (now at Brown Boveri) found such a blockade in 1968 as they were measuring the current-voltage characteristics of tunnel junctions containing isolated metal grains within the insulating barrier. (A tunnel junction consists of an insulator sandwiched between two conductors.) The two experimenters postulated that the observed behavior resulted from the electron charging effects. John Lambe (now at the Jet Propulsion Laboratory) and Robert Jaklevic (Ford Motors Scientific Laboratory) saw similar structure the next year. After a long hiatus, the electron charging effect is now attracting considerable attention because of improved experimental techniques and recent theoretical predictions of related phenomena.

Last year Theodore Fulton (AT&T Bell Labs, Murray Hill) and Gerald



Tunnel junctions. Three vertical aluminum electrodes overlap and contact the horizontal central electrode to form three junctions 0.03 μm wide. The capacitances are so small that the potential changes by about 0.4 mV when a single electron tunnels between any two junctions. (Scanning electron micrograph courtesy of AT&T Bell Labs.)

Dolan (now at IBM, Yorktown Heights) fabricated thin-film junctions whose areas and hence capacitances were unprecedently small. Using these junctions they made very clean observations of the single-electron charging effects.[1] Whereas in experiments on granular junctions done in the late 1960s, the capacitance was an average over grains of many sizes, the capacitance of the junction in the Bell Labs experiment was uniquely characterized by one value, and the size of the Coulomb blockade could be unambiguously correlated with the known capacitance. Also last year, Jeff Barner and Steven Ruggiero (Notre Dame),[2] and independently L. S. Kuzmin and Konstantin Likharev (Moscow State University),[3] studied electron tunneling in and out of very fine particles and found a new effect in the I–V curves that provides additional confirmation that electron charging is responsible for the observed effects.[4]

These observations fuel hope that experiments will soon observe a related phenomenon. According to theoretical predictions, if one biases a normally conducting tunnel junction with a steady-current source I_{dc}, the voltage across the junction should oscillate with a frequency equal to I_{dc}/e. Such oscillations are similar to the Bloch-wave oscillations predicted to occur in solids. If one applies a current bias to superconducting junctions, they should also exhibit such Bloch-like oscillations, but with a frequency of $I_{dc}/2e$. These oscillations would be different from, although analogous to, the ac Josephson effect, or the generation of oscillating currents when a dc voltage bias is applied across a Josephson junction. Because the frequency of the current oscillations in the ac Josephson effect depends on the applied voltage, the phenomenon is the basis for the present voltage standard. In a similar way, the Bloch-like oscillations, if found, might become the basis for a highly accurate current standard. One might possibly also exploit the electron charging effects to make electrometers or transistors that are sensitive to the charge of a single electron.

The Coulomb blockade

In a tunnel junction biased with a voltage V, an electron will gain an energy equal to eV as it crosses the barrier. At the same time, the junction has a capacitance C. Once the electron has tunneled, the potential difference across the barrier is reduced by $e/2C$. No current can flow as long as the bias voltage is less than the potential $e/2C$ associated with the loss of charging energy as the electron crosses the capacitor. For bias voltages below $e/2C$, the junction thus offers a very high resistance, so that the I–V curve has a very low slope in this region. This offset in the otherwise linear I–V curve is the signature of the Coulomb blockade for which the experimenters look. Fulton and Dolan exploited the oblique-angle electron-beam lithographic technique that Dolan developed at Bell Labs to produce thin-film tunnel junctions with areas on the order of $0.03\,\mu m \times 0.03\,\mu m$. Their device consisted essentially of three parallel electrodes forming adjacent junctions on a common transverse aluminum bar. (See the photo above.) The researchers studied the tunneling between only two of the three electrodes, so in effect they had a double tunnel junction. While the double junction complicates the analysis somewhat compared with that for a single junction, it decouples the system response from any capacitance the long leads might introduce into the experiment.

The I–V characteristic measured in the Bell Labs experiment shows clearly the expected Coulomb blockade (similar to the red and orange curves in the figure on page 21). The value of $e/2C$ determined from the width of the gap is 0.35–0.40 mV, corresponding to an effective capacitance of about 0.20–0.23 femtofarads. This compares with a value of 0.07–0.28 femtofarads estimated from the junction size and composition.

Using the same junctions, Fulton and Dolan tested a prediction made by Likharev[5] that the I–V characteristic would exhibit oscillatory behavior if a variable voltage were applied to the substrate of the double junction. The team at Bell found that the I–V characteristic varied in a periodic fashion as a function of this substrate voltage, as predicted. The location of the high-resistance region in the I–V curve shifts as the substrate voltage changes. After this substrate voltage increases by a fixed amount—the period of the oscillation—the pattern of I–V curves repeats itself. The explanation is that the voltage on the central electrode is a sum of terms, including one that is proportional to the substrate voltage and another that is proportional to the number of electrons on the central electrode. Increasing the substrate voltage by an amount equal to the period of the oscillation compensates exactly for the removal of one electron from the central electrode. Consequently, the junction behavior and the I–V curve repeat at periodic increases in the substrate voltage.

This modulation effect, while interesting, is not essential to demonstrating the electron charging effect. Fulton sees it as "icing on the cake." It does suggest, however, that the double tunnel junctions are operating as transistors that are sensitive to the charge of a single electron—albeit ones that are currently without gain. Likharev has pointed out that such very small transistors could potentially operate at high speed with low power consumption. Dolan believes that the charging effects will increase in importance and possible utility as the technology enables the fabrication of smaller and smaller systems. Phenomena that are regarded as nuisances in present devices could form the basis for a whole new set of devices on a smaller scale. As one decreases the capacitance one can increase the voltage at which the charging effects are noticeable and raise the temperature at which their effects can be employed for useful applications—perhaps even up to room temperature.

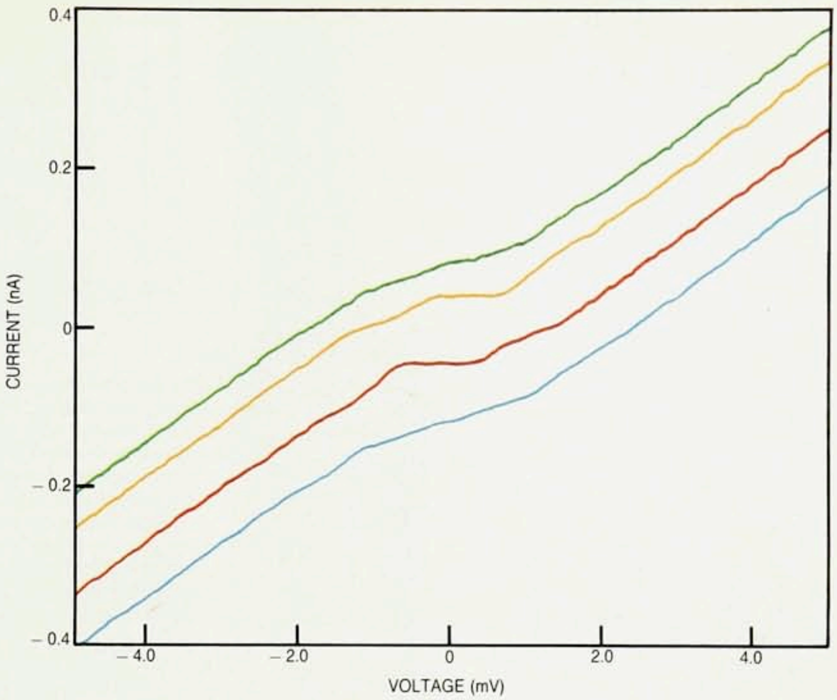
Coulomb staircase

To perform their experiment at Notre Dame, Barner and Ruggiero embedded ultrasmall (7.5 nm diameter) silver particles in insulating oxide films and sandwiched the films between two tunneling electrodes. The I–V curve measures the tunneling of electrons into and out of the silver particles, as in a double junction. The calculated capacitances of the particles are on the order of 6×10^{-18} F. The I–V characteristic displays not only the Coulomb blockade around zero voltage seen in the Bell Labs experiment but an entire "staircase" of discrete jumps in current. Each jump corresponds to the addition of an extra electron on a silver particle (see part a of the figure on page 22). Ruggiero notes that the experiment can essentially control the number of electrons on the particles. The voltage spacing, which should be e/C, cannot easily be determined from the curve but is readily apparent in the regular spacing of the spikes in plots of the conductance dI/dV (see part b of the figure on page 22).

Kuzmin and Likharev performed an experiment similar to that at Notre Dame using submicron indium grains having an average diameter of 100 nm embedded between two continuous thin-film electrodes.

A group at the University of Nijmegen, the Netherlands, has reported electron-charging effects in single as well as double series junctions.[6] The group, which consisted of Jan van Bentum, Herman van Kempen, Bart van de Leemput and Paul Teunissen, used a low-temperature scanning tunneling microscope to establish tunneling point contacts with variable capacitances on the order of 10^{-18} F or lower. They could change the capacitance, and thereby the size of the Coulomb gap, continuously by altering the distance between the tip and the sample. The observation of charging effects in a single-junction experiment was a pleasant surprise because even the experimenters expected that their results might be affected by the stray capacitance on the leads that couple the junction directly to the outside world.

The same group, with Richard Smokers, also of Nijmegen, has been able recently to measure the incremental charging of a single, isolated small particle. They deposited a layer of granular aluminum on a continuous film of oxidized aluminum and positioned the tip of the scanning tunneling microscope just above a single aluminum grain to form a double junction: The grain acted as the common electrode between the tip and the underlying aluminum film. The resulting I–V curve gives clear evidence of the Coulomb staircase.



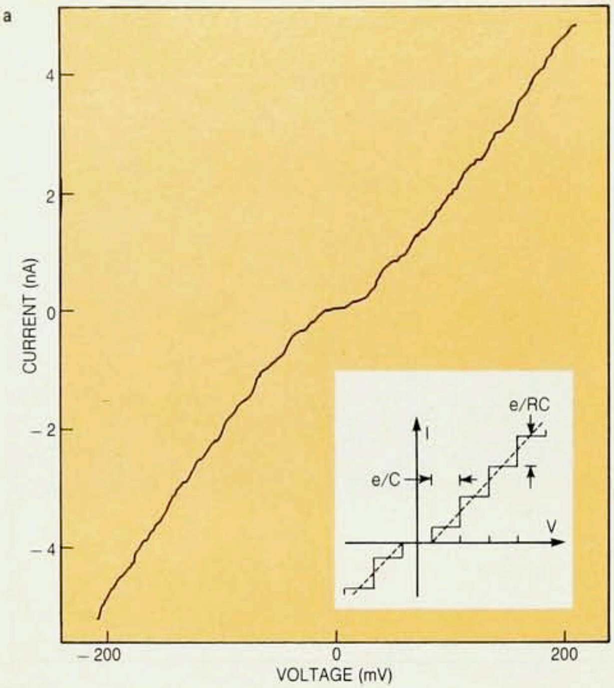
Current–voltage characteristic for a normally conducting thin-film tunnel junction at 0.2 K shows a region of high resistance near zero voltage (see red and orange curves). In this region voltages are below the capacitative charging energy associated with the tunneling of a single electron. As the voltage on the substrate of the junction is varied, the shape and position of the high-resistance region change. The pattern of change repeats in a periodic way every time the substrate voltage increases by a fixed amount V_M. Green curve results when the substrate voltage is 0.41 times V_M plus a constant; orange curve corresponds to 0.19 V_M; red to −0.18 V_M; and blue to −0.52 V_M. For each curve, zero voltage occurs at zero current, but curves have been vertically offset from one another for display. (Adapted from a figure supplied by AT&T Bell Labs.)

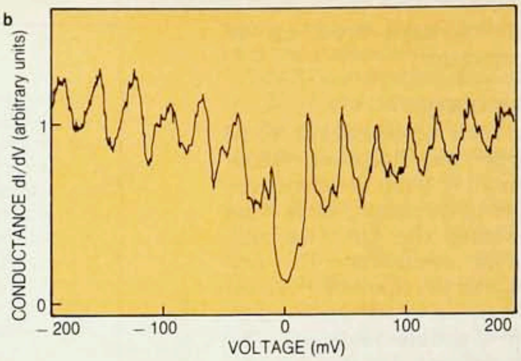
The current experiments are exploring a region of great interest to theorists. That region is the mesoscopic size scale—as Eshel Ben-Jacob (University of Michigan, Ann Arbor, and Tel Aviv University) described it to us. On the mesoscopic scale, the macroscopic and quantum phenomena overlap. Of particular interest is the competition in superconductors between the tunneling of single electrons, which represents localized behavior, and the tunneling of Cooper pairs, which have a finite size. A Harvard group has studied this competition with experiments on single junctions. The group included Marco Iansiti, Charlie Johnson, Walter Smith, Horst Rogalla, Chrisopher Lobb and Michael Tinkham.[7] In their experiment the electron charging energy was comparable to both the Josephson coupling energy and the thermal energy. When the Harvard team applied a magnetic field to decrease the strength of Josephson coupling, they saw evidence of the Coulomb blockade coexisting with other features common to Josephson tunneling.

Bart Geerligs and Hans Mooij of the Delft University of Technology, the Netherlands, have observed charging effects in two-dimensional arrays of aluminum tunnel junctions that are 190 junctions long by 60 junctions wide. An arrangement of many junctions in series has the same I–V characteristic as a single junction whose capacitance is much lower than that of the individual junctions of the series. Like the Harvard group, Geerligs and Mooij see suggestions of competition between charging effects and the Josephson coupling, especially at low temperatures in junction arrays with high impedances.

Bloch oscillations

The real aim of many of these experi-





Coulomb staircase (**a**) is a pattern of discrete jumps in the current at fixed intervals of voltage. Data shown are measurements of the *I–V* characteristic of 7.5-nm-diameter silver particles sandwiched between artificial tunnel barriers. The electron tunnels in on one side of the particle and out on the other. As shown in inset, voltage steps theoretically should be e/C wide after the first step, and the current steps should be e/RC high. Regularity of the staircase steps is more readily apparent in the plot of conductance (**b**), which shows periodic spikes. (Both figures adapted from ref. 2.)

ments now is to see a more dynamic effect—the equivalent of Bloch-wave oscillations in solids. These oscillations in solids occur when a constant electric field is applied to electrons in a periodic potential. Ben-Jacob explained the phenomenon to us with reference to a solid of cubic crystal structure spacing a in a constant external electric field: The applied field accelerates the electrons until they acquire a reciprocal wave vector **k** whose magnitude is π/a. But an electron of momentum π/a (in units of $\hbar$) may reverse its motion by giving a momentum of $\pi/2a$ to the lattice, that is, it may be reflected by the lattice. The resulting oscillations have never been seen in a solid because the electron scatters inelastically before it accelerates up to π/a. Furthermore, the motion of many electrons in the solid is incoherent.

In a current-biased tunnel junction, the electron sees a potential that varies periodically with time as one electron tunnels and more electrons subsequently move into the junction. In this periodic potential, the electron can shift between equivalent states, as the electron does in the case of Bloch oscillations in a solid. The constant-current source builds up charge on the junction until the voltage across the junction exceeds $e/2C$. An electron can then tunnel, reversing the voltage across the junction so that it becomes $-e/2C$. The current brings new charge to the junction, and the cycle repeats itself, with the voltage oscillating in each period. Ben-Jacob points out that in this mesoscopic size region, one can move charges into the junction continuously, although the charge can transfer across the junction only in discrete steps of one electron.

In 1982, Allan Widom and George Megaloudis (both then at Northeastern University), together with Terry Clark, Robert Prance and Helen Prance (all of the University of Sussex, England), suggested that Bloch-like oscillations might occur in superconducting tunnel junctions.[8] The concept was fully developed by Likharev and A. B. Zorin (Moscow State University).[9] Those two theorists in one paper[9] describe the Bloch-like oscillations in Josephson junctions as "just the process of a periodic discrete transfer of Cooper pairs between the junction electrodes, interposed by recharging of the junction capacitance by the external current." Ben-Jacob and Yuval Gefen (Weizmann Institute, Israel) have predicted that Bloch-like oscillations should occur in normal as well as superconducting junctions.[10]

One could in principle see these oscillations by detecting the emission of coherent radiation in the microwave region. They are far easier to see, however, if one applies external microwave radiation to beat against the oscillations. For a given applied frequency, there should be regularly spaced spikes in the current–voltage characteristic, corresponding to those values of the dc current where the frequency of the Bloch-like oscillations is in step with the applied frequency. Bloch oscillations have never been definitively seen in tunnel junctions, although Kazuo Yoshihiro, Joji Kinoshita, Katsuya Inagaki and Chikako Yamanouchi (all of the Electrotechnical Laboratory in Ibaraki, Japan) have used Bloch oscillations to interpret the results of their experiments on granular tin films.[11]

—Barbara Goss Levi

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