Special Surgery, New York, said that "All you can say is that grasping is consistent with arboreal behavior, but it doesn't rule out other behaviors." By way of analogy he said that although all flying birds have feathers, not all feathered birds fly. White, Lovejoy, and their colleagues liked this argument. Tuttle, Stern, Susman, and Jungers did not. Variously they pointed out that every primate with curved fingers and toes is arboreal and those that are terrestrial have straight toe and finger bones. "If you can show us a primate with curved phalanges that is not arboreal then we will accept your argument that we must think of alternative behaviors," challenged Stern. "Ours is the parsimonious position."

Bruce Latimer, of Kent State University, rejected tree climbing as a major adaptation because of the disappearance of the opposable great toe. He also suggested that curved lateral toes might be the result of stresses involved in toe-off in a bipedal gait that uses all digits and not just the first, as in humans. Lovejoy discounted climbing because, he said, with the anatomical sacrifices made toward bipedality in the lower limbs you would expect to see an enhancement of arboreal characters in the upper limb. "You don't," he asserted. "In fact there is a reduction of such characters."

Asked to describe how he thought *A. afarensis* moved, Lovejoy said it had "a unique mode of locomotion," a phrase that delighted the Stony Brook contingent. "This was a major concession," says Jungers. "He's always said it was completely modern before." Beyond saying the locomotion was unique, however, Lovejoy declined to be specific, a reluctance that Stern and his colleagues took to indicate an absence of ideas. "We shouldn't impose our ideas on the fossils," retorted Lovejoy. "We should let the fossils speak for themselves." Tuttle considered this statement to be not very helpful and said it was incumbent upon Lovejoy and his colleagues to present reasonable alternatives.

And so it went on, sometimes rather boisterously. Meanwhile, in his usual quiet demeanor, Henry McHenry, of the University of California at Davis, had pointed out that the postcranial morphology of *A. afarensis* at the Hadar was very similar to that of *Australopithecus africanus*, a presumed descendant. One so-far-undescribed finger bone of *A. africanus* from South Africa is said to be curved in the manner of Lucy's, but not to the degree. By contrast with the similarities in the postcranial skeleton, the head and teeth of these two species differ considerably. Whatever locomotor behavior is implied by the skeletal architecture of *A. afarensis* and *A. africanus* is, says McHenry, "a relatively stable adaptation." This stability might be taken to imply that the arboreal features retained are there not simply as evolutionary baggage but as important functional structures.

White contends that, as humans we are overimpressed by the features in the postcranial skeleton that are ape-like, which, he suggests, are relatively few. A chimpanzee would recognize how very human-like Lucy's skeleton is, he says.

Although the presentations revealed strong polarities among the main protagonists, it emerged that many observers would feel comfortable with a compromise position, an argument promulgated by Tuttle. He sees *A. afarensis* as having had an essentially modern bipedal gait while retaining significant anatomical adaptations to arboreality.

Tuttle was, however, pretty much alone on another issue, that of whether the feet of *A. afarensis* as seen in the Hadar foot bones could have made the footprints at Laetoli. White, who was involved in excavating the prints, thinks they could, because, he says, the feet and the prints are essentially modern in form. Stern and Susman also think they could, but in this case it is because they see the feet and the prints as those of a climbing animal. Tuttle, who has studied the prints in detail, says the feet and the prints don't match, principally because he would expect the curved toes to have left a distinct impression. There is no such impression.

White and a graduate student Gen Suwa have reconstructed a Lucy-sized foot, based on inferences from bones at Hadar and Olduvai Gorge, and demonstrated that the diminutive foot would indeed fit within the diminutive prints at Laetoli. Nevertheless, the absence of deep impressions from the lateral toes still left Tuttle unimpressed. "The Laetoli prints are much more human-like than can be inferred from the Hadar foot bones," he says. "If someone were to find curved toes at Laetoli I would change my mind, but not until then."

Lucy's fingers and toes really did cause some problems.—**Roger Lewin**

Fractional Quantum Numbers in Solids

A new theory explains how electrons in solids in strong magnetic fields at cryogenic temperatures form a liquid with fractional quantum numbers

The semiconductor silicon, the material on which the microelectronics industry is largely built, is probably the best understood of all solids. Another semiconductor, gallium arsenide, is fast catching up. So, it is fitting that solid-state physicists were astounded 3 years ago by reports of a new physical phenomenon in these materials with the name quantum Hall effect. Then last year, as the excitement over the quantum Hall effect was being replaced by a satisfactory theoretical understanding of the unusual behavior, Daniel Tsui of Princeton University and Horst Stormer and Arthur Gossard of Bell Laboratories raised the ante with their report of the "fractional" quantum Hall effect in gallium arsenide that they cooled to 2 K or less and subjected to intense magnetic fields of about 15 tesla.

Now the interest has shifted to a new finding by theorist Robert Laughlin of the Lawrence Livermore National Laboratory concerning the origin of the fractional quantum Hall effect. Whereas the electrons responsible for the quantum Hall effect act as if they were weakly interacting particles in a gas, those giving rise to the fractional quantum Hall effect act as if they were very strongly interacting particles in a liquid. Theorist Bertrand Halperin of Harvard University says that, if Laughlin's explanation turns out to be right, it would mark a fundamentally new way to think about the way electrons can cooperate in a solid. Although there are no obvious technological applications for the fractional quantum Hall effect right now, the intellectual novelty is comparable to that of the quantum theory of superconductivity

(BCS theory) that was developed in the mid-1950's, according to Halperin.

The ordinary Hall effect dates back to 1879 when Edwin Hall of Johns Hopkins University discovered that a voltage was induced transversely across a gold foil carrying an electric current while immersed in a magnetic field oriented in a direction perpendicular to the foil. The Hall voltage, as it is now known, is due to the tendency of electrons to spiral around magnetic field lines, which causes them to pile up on one side of a current-carrying metal or semiconductor. The magnitude of the voltage ordinarily varies linearly with the strength of the magnetic field.

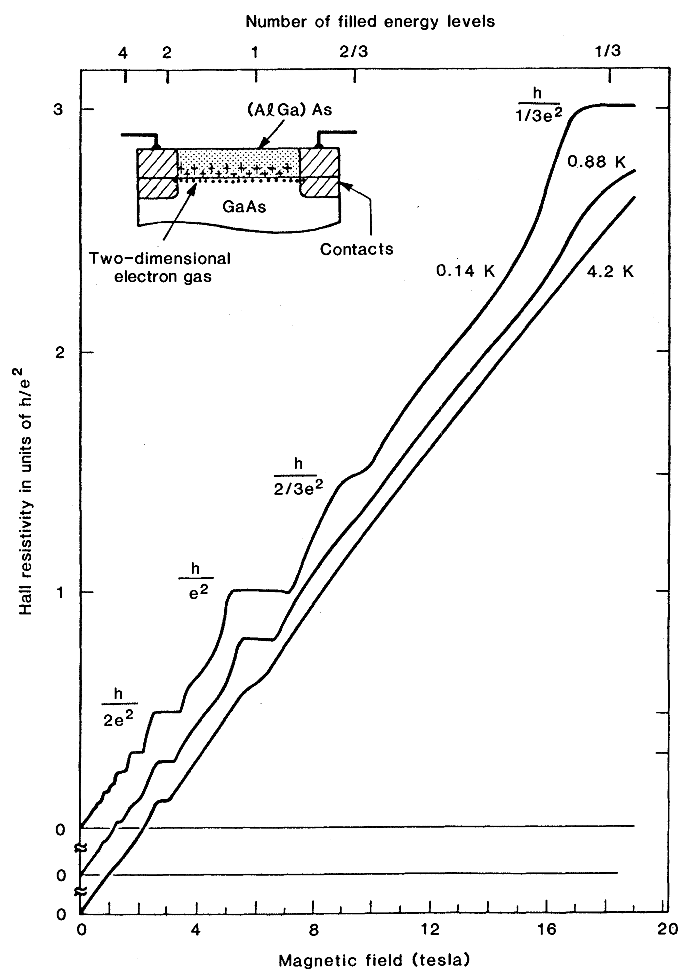
The Hall effect became vastly more interesting in 1980, when Klaus von Klitzing of the University of Würzburg in West Germany, Gerhard Dorda of the Siemens Research Laboratories in Munich, and Michael Pepper of the Cavendish Laboratory of the University of Cambridge published their findings that the Hall voltage could become quantized in a certain type of silicon transistor. In particular, the Hall resistivity, defined as the ratio of the Hall voltage to the current, took on values equal to h/e^2i, where h is Planck's constant, e is the charge of an electron, and i is an integer or quantum number. For technical reasons, the investigators did a slightly different experiment, but the results are equivalent to the statement that rather than varying smoothly with the strength of the magnetic field, the Hall voltage exhibited "steps" at the quantized values corresponding to successively lower values of i as the field strength increased. A few months later, Tsui and Gossard reported the same quantization of the Hall resistivity in a multilayered structure consisting of gallium arsenide and aluminum gallium arsenide.

Experimentally, the fractional quantum Hall effect differs from its more conventional cousin only in that the integer i in the Hall resistivity is a rational fraction. So far, the denominator is always an odd integer. To see why this poses a problem to solid-state theorists, it is necessary to look further at how electrons behave in semiconductors.

Most of the time, the free electrons in a semiconductor act like a gas. They can occupy any energy state in a semicontinuous band (the conduction band) and the interactions between one electron and another are unimportant. For the quantum Hall effect, this three-dimensional gas must be converted into a two-dimensional system. In silicon, this is achieved in the so-called metal-oxide-silicon field effect transistor or MOSFET. The concentration of electrons in a thin layer of silicon underneath the oxide is controlled by the magnitude of a positive voltage applied to a metal contact over the oxide. Although the thickness of the layer may be 25 angstroms or more, the quantum mechanics works out in such a way that the electrons are constrained to motion in the plane parallel to the silicon-oxide interface and thereby become mathematically a two-dimensional system. In the case of the gallium arsenide–aluminum gallium arsenide multilayer structure, the electric field at the interface between the layers is sufficient by itself to confine electrons to a thin layer in the gallium arsenide. The concentration of electrons is fixed not by an externally applied voltage but by the concentration of impurity or doping atoms in the aluminum gallium arsenide, which donate electrons.

Next, the strong magnetic field is applied perpendicular to the interface. The field has the effect of breaking up the conduction band into several discrete energy levels. Roughly speaking, the electrons in quantum states of a particular energy level orbit the magnetic field lines with a radius fixed by the field strength and the energy. The number of quantum states or orbits in a given energy level is equal to the number of magnetic field lines or flux quanta and hence increases linearly with the magnetic field strength, while the number of electrons available to occupy these states is fixed. In the quantum Hall effect experiment, as the magnetic field strength is swept from a low to a high value, the Hall resistivity is quantized for those values of the field for which the number of orbits exactly matches the number of electrons. At the highest field, the number of orbits is so large that only those in the lowest energy level are filled and $i = 1$. At a lower field, there are fewer orbits per energy level, so that the two lowest levels can be filled, and $i = 2$, and so on. An interesting twist is that impurity atoms are necessary to maintain the quantization condition over wide ranges of field strength (needed to see steps) when the number of electrons and the number of orbits do not exactly match by in effect soaking up the excess electrons.

As the magnetic field strength increases indefinitely, Tsui explained to *Science*, the electron orbits should shrink until their radii eventually approach zero and the electrons are "frozen" in place. Physicists call this an electron solid. Moreover, since the number of electron orbits at the lowest al-



Fractional quantum numbers

The Hall resistivity of a two-dimensional electron gas in a gallium arsenide-aluminum gallium arsenide multilayer structure exhibits "steps" at certain values of the magnetic field. The Hall resistivity is equal to h/e^2i *on the steps. As the temperature is lowered below 4.2 K, steps corresponding to fractional values of the quantum number* $i = 1/3$ *and* $2/3$ *appear. The plus marks in the aluminum gallium arsenide refer to the ionized donor impurities that supply electrons to the gallium arsenide.*

lowed energy level also continues to increase and can therefore never be completely occupied, there should be no quantization of the Hall effect for magnetic fields stronger than that needed to achieve the $i = 1$ quantization.

What Tsui, Stormer, and Gossard found, when they journeyed to the National Magnet Laboratory at the Massachusetts Institute of Technology in order to find high-field magnets of the type needed to test this hypothesis, was that steps in the Hall resistivity did occur and that they corresponded to a value of the fractional quantum number $i = 1/3$. Subsequent experiments at the magnet laboratory by these researchers and their colleagues have found other values of i for which quantization is indicated; $i = 2/3$ came next, for example. In some of the cases, the evidence is as yet incomplete. The researchers see dips in the resistivity in the direction of the current for $i = 2/5$, 3/5, and 4/5, but only for $i = 2/5$ was there observable structure in the Hall resistivity. The evidence for $i = 1/3$, however, is ironclad. The Hall resistivity equals $3e/h^2$ to at least 1 part in 10^4.

Could fractional quantization be compatible with the formation of an electron solid? Apparently not, because calculations by several solid-state physicists have shown that the energy associated with an electron solid varies smoothly with the number of electrons; there is no preference for a solid in which there is exactly one electron orbiting three magnetic field lines.

A new line of thinking, according to theorist Steven Girvin of the National Bureau of Standards, started from the observation that these calculations may not have properly taken account of the interactions between electrons. In an electron gas, one can calculate the motion of each electron as if it were an independent particle moving in an electrostatic potential energy given by the positively charged ions that are fixed in position and by all the other negatively charged electrons. The electrons are not fixed in place, so the potential energy changes with time. But, if the interactions are weak enough, an average potential energy can be constructed. If the interactions are strong, however, they cannot be accounted for by a time average, and the motions of each electron cannot be calculated independently but all must be calculated together. In quantum mechanics, this is called a many-body problem.

In the meantime, Dajiro Yoshioka at Bell Laboratories (now at the University of Tokyo), Halperin of Harvard, and Patrick Lee of the Massachusetts Institute of Technology temporarily discarded the idea of analytically obtaining the electron motions (or wave functions in quantum mechanics) and settled for numerically solving the problem of the energy of a few (four to six) electrons in a box pierced by a magnetic field. The theorists found in fact that the energy per particle of their model system was lower than that calculated previously for an electron solid. Moreover, the energy did not vary smoothly with the filling of the lowest energy level but showed a kink at $i = 1/3$, suggesting an especially favored configuration there. Finally, they investigated certain symmetry properties of their electron system and found them to be different from that expected for a crystal. All in all, the authors interpreted their results to mean that the most stable state of the electrons responsible for the fractional quantum Hall effect was more likely to be a liquid than a solid.

It is a fundamentally new way to think about the way electrons cooperate in a solid.

Laughlin's contribution to the riddle of the fractional quantum Hall effect was presented at the American Physical Society's March meeting in Los Angeles to an overflow crowd.

What Laughlin presented was a many-body quantum mechanical wave function that describes the electrons in a semiconductor immersed in a high magnetic field. Since many-body problems in either classical or quantum mechanics are not exactly soluble, Laughlin's solution was arrived at by intuition, in part. The wave function he found represents a partial solution in that it corresponds explicitly only to certain electron concentrations. This wave function, however, describes an unusual liquid rather than a gas or a solid. One of the properties of the liquid is that its excited quantum states seem to correspond to "particles" with fractional electronic charge. It is also a so-called quantum liquid like liquid helium that never becomes solid, even as its temperature approaches 0 K. It fails to solidify because the small amount of particle motion and associated "zero-point energy" that quantum mechanics prescribes must persist at zero temperature are sufficient to prevent the particles from freezing into a solid.

The wave function describes an electron liquid rather than a solid because the electrons are distributed spatially uniformly throughout the semiconductor. It describes a liquid rather than a gas because the electron motions are highly correlated as a result of the electron-electron interactions. One manifestation of this correlation is the r^3 dependence of the wave function on the separation between any two electrons; that is, the electrons strive mightily to stay apart while maintaining the uniform spatial distribution. This feat requires a high degree of cooperation on their part.

A key feature of the electron liquid is that it exists only when the electron concentration is one-third (or one-fifth, one-seventh, and so on) that of the magnetic field lines. Equivalently, it exists when the number of electrons is exactly one-third the number of quantum states in the lowest energy level of the ordinary two-dimensional electron gas. Any deviation from this ratio costs energy. It is this property that gives the liquid its lower energy and thereby makes it more stable than an electron solid. It also makes the liquid incompressible. The fractional quantum Hall effect is seen only when the liquid state exists.

One way of visualizing the idea of excited states with fractional electronic charge is as follows. One can put in the energy needed to make an excited state by trying to increase the magnetic field by one flux quantum. Since the density of flux lines is uniform, the addition of one more pushes the nearby lines slightly away. All the flux quanta except the added one have one-third of an electron associated with them. Thus, locally in the area of the added quantum there is one-third fewer electron.

Laughlin has several tests that provide evidence for his wave function. The energy of the liquid is lower than that of any solid calculated so far, and the energy per particle is consistent with that found by Yoshioka, Halperin, and Lee. And Halperin reported in March at the European Physical Society meeting in Lausanne, Switzerland, an extension of Laughlin's wave function into a more complicated entity capable of accounting for the fractional quantum Hall effect with a variety of rational fraction values of i. A symmetry property already guarantees that Laughlin's wave function also applies to values of $i = 1 - 1/n$.

All in all, while many theorists are now at work on the problem, it is too soon to say that the problem of the fractional quantum Hall effect has been solved. The excitement is that what looks like a promising start is also a new window on the intimate life of electrons in solids.—**Arthur L. Robinson**