Figure 2 **Lorisiforms here and now — a bushbaby (left) and a loris.**

LEFT: CLEM HAGNER; GALLO IMAGES/CORBIS; RIGHT: K. A. I. NEKARIS

bushbabies commonly leap actively and show conspicuous elongation of the tarsal bones of the hindlimb. Isolated tarsals from *Progalago* show moderate elongation, but in the absence of limb-bone fossils of *Saharagalago* or *Karanisia*, we cannot say whether these earlier forms already showed the expected divergence in locomotion. Modern bushbabies also clearly differ from lorises in possessing molar-like posterior premolars. The discovery of similar teeth in *Saharagalago* would provide a valuable additional test of the inferred relationship to modern bushbabies.

*Saharagalago* and *Karanisia* are the latest discoveries in four decades of fossil-hunting by Elwyn Simons and colleagues in the Fayum Depression. The Fayum site, on the eastern margin of the Sahara in Egypt, contains extensive sediments spanning the late Eocene and the early Oligocene. It provides the best known record for the early evolution of modern mammals in Africa. This single site has yielded a remarkable diversity of primate fossils, most being of higher primates, although previous finds include *Afrotarsius* (possibly related to modern tarsiers) and *Plesiopithecus* (an aberrant early strepsirrhine offshoot).

More broadly, Seiffert and colleagues[1] conclude that the new finds are compatible with a date of 50–53 million years ago for the last common ancestor of strepsirrhines, with Afro-Arabia being the location of that ancestor. But this conclusion stems from a direct reading of an inadequate fossil record. We still have no fossil primates from sub-Saharan Africa before the Miocene, and the fossil record for Madagascar lemurs remains nil. My own alternative interpretation stems from statistical considerations[8] indicating that such gaps in the primate fossil record have led to a serious underestimation of divergence times. Furthermore, molecular phylogenies for placental mammals[9] have revealed a group of endemic African mammals (Afrotheria) that does not include the primates, suggesting that primates originated elsewhere. Various molecular trees also indicate that primates originated much earlier than generally accepted, about 90 million years ago. One possibility is that strepsirrhines originally inhabited Indo-Madagascar, rather than Africa, and that lemurs became isolated when Madagascar separated from India. Subsequently, lorises could have migrated to Africa after India collided with Asia, reaching Africa during the Eocene.

Interestingly, the only known fossil primate with direct affinities to lemurs (*Bugtilemur*; Fig. 1) was reported from Oligocene deposits in Pakistan[10]: its dentition closely resembles that of modern dwarf lemurs. *Bugtilemur* raises more questions than it answers, however, and shows that we still have much to learn about the early evolution of our primate relatives. ■

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**Quantum physics**

# Wheels within wheels

Jurgen H. Smet

Quasi-particles, an ingenious dodge used to simplify calculations on vast systems of interacting particles, seem to account for the fractional quantum Hall effect. But do we now need a further generation of quasi-particles?

Problems involving many strongly interacting bodies are pervasive in physics. For instance, in a cubic centimetre of condensed matter, typically $10^{23}$ electrons repel one another and interact with a comparable number of positively charged nuclei. The motion of one electron elicits a response from all of the others. So it is no wonder that the search for an exact solution is usually a desperate undertaking. Ingenious recipes have been developed, based on quantum field theory, to tackle these problems: they identify fictitious entities — quasi-particles — that recast the system of strongly interacting real bodies into a simpler one, composed of weakly or even non-interacting bodies, while still capturing the essential physics. Landau's quasi-electrons — bare electrons dressed with a cloud of positive charge — are a celebrated example that successfully describes the behaviour of metals. More recently, composite fermions[1] — electrons in a different guise — have emerged to account in single-particle terms for the fractional quantum Hall effect[2], an electron–electron correlation phenomenon *par excellence*. Pan *et al.*[3] now report in *Physical Review Letters* that the story goes on: apparently, residual interactions among these composite fermions produce a second generation of composite fermions.

Quantum Hall effects[4,5] arise when electrons constrained to move in a plane are exposed to a perpendicular magnetic field. They are quantum mechanical descendants of a classical effect discovered by Edwin Hall more than a century ago. He observed that a current-carrying conductor in the presence of a field develops a voltage that is perpendicular to both the current flow and the field. Ever since, a measurement of the Hall voltage has been a valuable characterization method in solid-state physics, because it reveals the number as well as the sign of current-carrying charges. Its application to clean, near-perfect two-dimensional conductors at low temperatures brought a new twist. Here, the Hall voltage does not simply rise linearly with the applied field. Instead, it shows plateaux, as if the Hall voltage is frozen near specific field values (Fig. 1, overleaf). Across the plateaux, the voltage drop in the direction of the current flow vanishes; this is the second hallmark of the quantum Hall effects.

The magnetic field sends the electrons into circular orbits. In classical physics, any radius is allowed. Quantum mechanics, however, dictates discrete values for the radius, much as it imposes distinct Bohr orbits on an atom. This is an outcome of the discrete character of magnetic flux: the applied field derives from many flux quanta, each contributing the smallest unit of magnetic flux to the total. According to the laws of quantum mechanics, only electron orbits that enclose exactly one such quantum or multiple quanta of magnetic flux are legitimate. Like the Bohr orbits, each of these orbits has a discrete energy associated with it — a Landau level. At fixed field, the larger the radius of an orbit, the higher its energy. The electrons are distributed among the orbits or Landau levels so as to minimize the total energy, keeping in mind that each orbit fits only one electron. However, many orbits of equal size (and thus energy) are spread throughout the sample. To be precise, each Landau level can accommodate as many

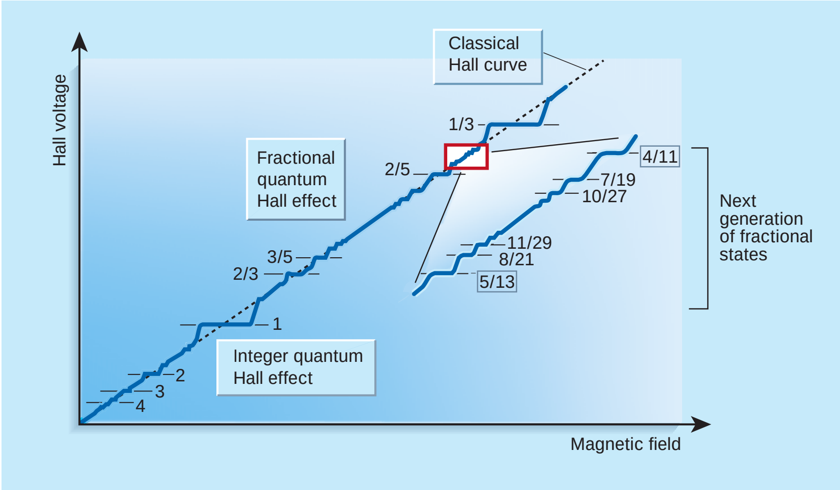


Figure 1 **The Hall effect. The Hall voltage develops when driving a current through a conductor exposed to a perpendicular magnetic field. In classical physics, it follows a straight line. But quantum mechanics forces the electrons to occupy discrete energy levels. Whenever an integral number of these levels is filled, a plateau appears in the Hall voltage. At higher fields, when the lowest level is only partially filled, additional plateaux arise by virtue of interactions among the electrons — the fractional quantum Hall effect. This is equivalent to the integer Hall effect for 'quasi-particles' made up of an electron plus two flux quanta. But it can be taken further: add two more flux quanta to the composite quasi-particle, and you might expect new plateaux at, for instance, the fractions shown in the enlargement (schematic only; the plateaux are yet to be confirmed). Pan *et al.*[3] have seen signs of some of these new fractional states (in boxes). With increasing sample quality the number of plateaux seems to grow, such that the Hall curve starts to show fractal characteristics.**

electrons as the total number of flux quanta that thread the sample. As the field is raised and the number of flux quanta increases, Landau levels can take up ever more electrons, and higher energy levels are successively depopulated. The filling factor $\nu$ denotes the number of filled levels. When $\nu$ takes on an integer value, the system will resist the addition of an extra electron, as it must broach a new Landau level with higher energy. This 'incompressibility' is at the heart of the integer quantum Hall effect[4].

Its cousin, the fractional quantum Hall effect[5], ensues mainly at higher fields when one Landau level is occupied and the filling takes on a fraction that can be expressed as a ratio of integers, $\nu = p/q$, with $p$ and $q$ integers. Despite its experimental resemblance, it cannot be accounted for directly in the above picture, considering only the motion of a single electron. If the one occupied level is only partially filled, why the incompressibility? Early on, it was recognized that all electrons must participate to bring about this effect[6]. At many of these fractional fillings, electrons apparently succeed in becoming arranged within the Landau level so as to significantly reduce their mutual repulsion.

Much later, it was realized that there is no need to track all electrons to understand this phenomenon. At high fields, compound particles come on the scene, each assembled from an electron and two flux quanta[7] (or more generally, an even number of them). This bond between electrons and flux quanta turns out to be a natural way for electrons to avoid one another, and the resulting quasi-particles, named composite fermions, may for many purposes be viewed as non-interacting. They, too, are forced by a field into circular orbits, which must obey the laws of quantum mechanics[8]. But, unlike electrons, they experience only an effective field, greatly reduced from the applied field by an amount equal to the field produced by all the flux quanta of their fellow composite fermions. The discrete orbits again have associated Landau levels. Filling these gives the integer quantum Hall effect for composite fermions. Sure enough, it occurs at precisely those applied fields where the fractional quantum Hall effect is routinely observed.

Now Pan *et al.*[3] have demonstrated experimentally that this can be taken still further. A partially filled composite fermion level may in turn bring forth a new generation of composite fermions. At fillings between 1/3 and 2/5, two Landau levels of two-flux-quanta composite fermions are filled, one completely, the other partially. Pan *et al.* observed precursors of the fractional quantum Hall effect associated with those composite fermions in the partially filled level. This can be understood if composite fermions collect an extra pair of flux quanta to form four-flux-quanta composite fermions instead, which — as one might guess by now — undergo the integer quantum Hall effect. The other two-flux-quanta composite fermions in the completely filled level are left intact and cohabit with the higher-order composite fermions.

Sample imperfections and the quantum Hall effect suffer a love–hate relationship. Disorder is essential to bring out wide plateaux in the Hall voltage, but too much will overwhelm and destroy more fragile quantum Hall states. The new fractional states, unveiled by further reducing sample imperfections, are in strength and appearance a natural progression from previously reported states. As crystal growers achieve ever lower levels of disorder, and laboratories reach ever lower electron temperatures, we may expect to see additional fractional states. The data of Pan *et al.*[3] support an iterative scheme, where composite fermions in a partially filled level accumulate a growing number of flux quanta, as an intuitive algorithm to predict the next sequence of states to be discovered. This straightforward picture is enticing, and works marvellously for the fractional quantum Hall states discerned so far. But it has no rigorous foundation. Indeed, preceding theoretical work outside[9,10] and within[11] the framework of composite fermions suggests that some of the newly discovered states are unstable. There is clearly a need to reconsider these issues and to examine the residual interactions that might prompt the mutation into higher-order composites.

The recurring pattern of transforming fractional into integer quantum Hall states also bears on the geometrical properties of the Hall curve itself. As pointed out some time ago[12], the curve shows self-similarity, as it unfolds like a fractal[13], ever more detail being added as sample quality improves. It seems that the integral quantum Hall curve has been applied as a 'fractal generator' or template[12], the iterative flux attachment translating into the sequential replacement of segments with transformed copies of the template (Fig. 1). The work by Pan *et al.* urges us to pay more attention to this fractal-like structure: it may guide us to a deeper understanding of the quantum Hall effects. ■

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