now, and might be best approached by using a dual-beam optical trap, which is better for detecting short-range movements and has already been used to detect single myosin movements[14]. ■

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Quantum Hall effect

Composite fermions pair up

Nick Bonesteel

In 1956 Leon Cooper[1] published a simple 'back of the envelope' calculation that provided a key insight into the nature of superconductivity. Cooper was interested in the quantum-mechanical description of electrons in a metal. Electrons are fermions — particles which obey the Pauli exclusion principle forbidding two identical particles from being in the same quantum state. Because of this, at low temperatures and in the absence of any instability, a gas of electrons will form something called a Fermi sea. Cooper knew that although electrons normally repel each other, in a metal they can feel a net attraction due to tiny lattice vibrations (phonons). He then showed that if such an attraction is present, two electrons added to a Fermi sea will always form a 'molecular' bound state called a Cooper pair. This result was an important step towards the development of the full Bardeen–Cooper–Schrieffer (BCS) theory of superconductivity. On page 863 of this issue, Scarola *et al.*[2] present a modern version of Cooper's calculation in a new and surprising context, that of the quantum Hall effect.

The quantum Hall effect is the modern offspring of an observation first made by Edwin Hall in 1879. The Hall effect occurs when a conductor carrying an electrical current is put in a magnetic field and a voltage develops perpendicular to both the current and the field. The sign of the Hall voltage reveals whether negative or positive charges are carrying the current. Later experiments at very low temperatures and in high magnetic fields led to a quantum version of this effect in a two-dimensional conductor. Under these conditions, the gas of electrons is trapped in two dimensions and the voltage changes in quantized steps (rather than smoothly) as the magnetic field is increased.

Physicists often measure the strength of a magnetic field in natural units called magnetic flux quanta. A two-dimensional gas of electrons in a magnetic field is then characterized by its 'filling fraction' ν — the number of electrons per flux quantum. The quantum Hall effect can occur when the filling fraction is an integer, $\nu = p$ (integer quantum Hall effect), or a rational fraction, $\nu = p/q$ (fractional quantum Hall effect).

When the quantum Hall effect occurs, the electron gas becomes incompressible — the density of particles becomes fixed or 'pinned' at a specific value. For the integer effect, this pinning can be understood in terms of non-interacting electrons obeying the Pauli exclusion principle. But for the fractional effect, the Coulomb repulsion between negatively charged electrons must be included in the calculation. As shown by Robert Laughlin, this repulsion can lead to subtle correlations in the electrons' behaviour that allow them to condense into an incompressible quantum fluid at certain rational filling fractions.

New insight into the nature of the quantum Hall effect was provided when Jain introduced the composite fermion[3]. This can be thought of as an electron bound to an even number of magnetic flux quanta (or vortices). Like electrons, composite fermions obey the Pauli exclusion principle. But unlike electrons, composite fermions see an effective magnetic field that is much smaller than the applied magnetic field. Accordingly,

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Behavioural ecology

Eat me!


HEATHER ANGEL

The parasitic fluke *Microphallus piriformes* has a problem. To complete its life cycle it needs to travel between two hosts: the rough periwinkle (*Littorina saxatilis*, pictured, a seashore mollusc) and the herring gull. In the normal run of things, these species have little to do with each other. But the cunning parasite has a way of making introductions.

By comparing the behaviour of infested and healthy periwinkles, Helen McCarthy and colleagues have discovered that *M. piriformes* seems to bend the periwinkles' behaviour to its own ends. In both the laboratory and field experiments on Muck Island, Scotland, parasitized periwinkles showed a greater tendency to crawl upwards — into positions where they are more visible to gulls, and presumably more likely to be eaten by them — than their healthier counterparts (*Anim. Behav.* **59,** 1161–1166; 2000).

To reach their elevated positions, the suicidal periwinkles reduce their amounts of horizontal and downwards travel. It is the direction, rather than the amount, of movement that changes. Infected animals also alter their responses to the tide, moving upwards as it rises — healthy periwinkles do the opposite.

This change in behaviour happens only when the infection is mature and the fluke is ready to switch hosts. In the early stages, infected periwinkles behave normally; after all, the parasite doesn't want its home to perish from desiccation or predation too early. The parasite's timing also seems designed to bring periwinkles and gulls into contact during the summer, when gulls are gathered at their breeding colonies. The proportion of parasitized periwinkles is much greater near gull breeding colonies than at their foraging sites, although McCarthy *et al.* have yet to show whether infested periwinkles are actually more likely to find their way into a gull's stomach.

Nor are vertebrates immune to this form of parasitic trickery. A paper by Manuel Berdoy and colleagues, published earlier this month (*Proc R. Soc. Lond. B* **267,** 1591–1594; 2000), shows that rats infected with the protozoon *Toxoplasma gondii*, which they catch from eating cat faeces, become more curious and less fearful. This makes them easier prey for cats — enabling *Toxoplasma* to get back to its preferred host. **John Whitfield**

Jain showed that the fractional quantum Hall effect for electrons can be seen as an integer quantum Hall effect for composite fermions.

A striking consequence of this theory is that for a filling fraction $\nu = 1/2$, the effective magnetic field seen by composite fermions is zero[4]. It is then possible for composite fermions to form a Fermi sea, analogous to the Fermi sea of electrons in an ordinary metal. This description is consistent with the observation that the $\nu = 1/2$ state is compressible — that is, it does not show the quantum Hall effect. Other experiments around $\nu = 1/2$ have revealed behaviour characteristic of a two-dimensional metal in zero field[5].

Composite fermion theory predicts that at a filling fraction of $\nu = 5/2$, the effective magnetic field should also be zero. But experiments show a quantum Hall effect at $\nu = 5/2$ (refs 6, 7), suggesting that this is not a simple metallic state. An intriguing possibility[8,9], and one that has recently gathered theoretical support[10,11], is that at $\nu = 5/2$ a Fermi sea of composite fermions forms but is susceptible to Cooper pairing and so becomes a composite fermion 'superconductor'.

Why would such pairing lead to a quantum Hall effect? One way to understand this is in terms of the Meissner effect — the fact that superconductors expel magnetic fields. If a Fermi sea of composite fermions does form a 'superconducting' state of Cooper pairs, then, because adding more electrons to the system is equivalent to applying a magnetic field, any added particles will be expelled. This leads to just the sort of pinning density needed for the quantum Hall effect.

With this in mind, Scarola *et al.*[2] have carried out a Cooper calculation for composite fermions. Unlike Cooper's original work, this was too difficult to do on the back of an envelope. Instead, Scarola *et al.* explicitly constructed quantum wavefunctions for the relevant composite fermion states and calculated their energies numerically. Using this technique they could start with a Fermi sea of composite fermions, introduce (or remove) two composite fermions, and compute the binding energy of the added (or removed) pair. Their results show that at $\nu = 1/2$ the composite fermions do not bind, but at $\nu = 5/2$ they do, suggesting Cooper pairing.

Given that the only interaction between the particles in this model is their Coulomb repulsion, it is natural to wonder about the origin of the attractive interaction causing Cooper pairing. Scarola *et al.* attribute it to an 'overscreening' of the Coulomb repulsion that occurs when the negatively charged electrons bind to the positively charged magnetic vortices to become composite fermions. Roughly speaking, because the short-range part of the effective Coulomb repulsion between electrons at $\nu = 5/2$ is weaker than at $\nu = 1/2$, Scarola *et al.* argue that it is possible for there to be a residual attractive interaction between composite fermions at $\nu = 5/2$ but not at $\nu = 1/2$.

Scarola *et al.*'s calculation is a beautiful demonstration that a Fermi sea of composite fermions can form Cooper pairs, and gives some insight into why such pairing occurs at $\nu = 5/2$ but not $\nu = 1/2$. Like Cooper's 1956 calculation, this is an important step forward in our understanding of the $\nu = 5/2$ state, but it is not yet a full BCS theory of composite fermion pairing. It is possible that such a theory, when it arrives, may help explain another phenomenon in which pairing arises from purely repulsive interactions — high-temperature superconductivity. ■

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Neurobiology

Frazzled precision guides axons

Roman J. Giger and Alex L. Kolodkin

A functional nervous system depends on an intricate, finely tuned network of neuronal connections. During development, axons and dendrites, the specialized projections of a neuron, extend from the neuronal cell body over what are often long distances to establish contact with their targets. To ensure accurate targeting, axons and dendrites use attractive and repulsive guidance cues along their trajectories. Using the fruitfly *Drosophila melanogaster* as a model system, Hiramoto and colleagues, writing on page 886 of this issue[1], offer mechanistic insight into how secreted, diffusible cues can provide precise guidance information. The authors show that a member of the Netrin family of diffusible guidance proteins is captured far from its site of synthesis and presented to approaching axons by its binding partner, a protein called Frazzled. The Netrin protein thereby instructs growing axons to follow a precise trajectory within the central nervous system (CNS).

The neuronal growth cone — a subcellular structure at the leading end of extending nerve fibres — integrates a myriad of guidance cues, and responds by dynamically adjusting the overall direction in which

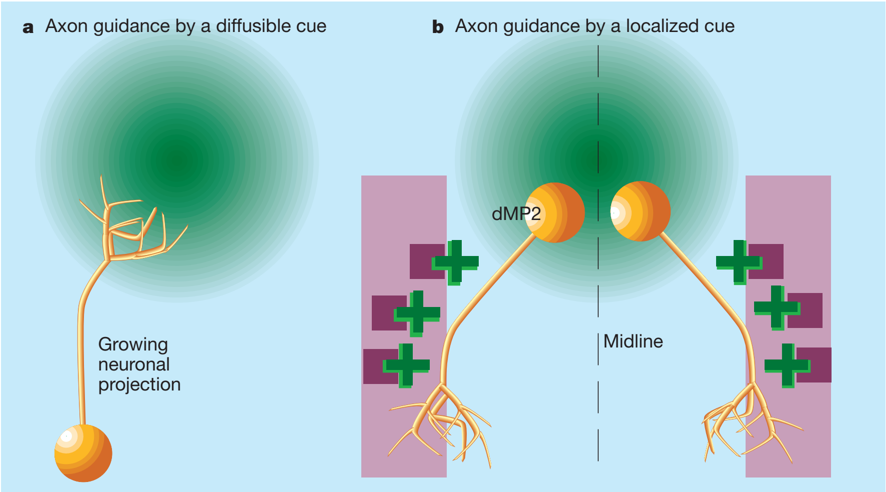

Figure 1 **Guiding axon trajectories in developing embryos.** a, **Some axons respond to smooth gradients of attractive guidance cues (green)** ***in vitro*** **and** ***in vivo*****. Presenting guidance cues in this way does not allow for abrupt changes in axon trajectory.** b, **If a secreted attractive guidance cue is selectively localized to an intermediate axonal target, guidance events far from the site at which the cue is made can be controlled accurately. For example, in the** ***Drosophila*** **embryo, dMP2 neurons extend laterally away from the midline and then turn posteriorly in a dorsolateral region of the central nervous system (CNS). This turn requires the chemoattractant Netrin (green plus symbols). The Netrin receptor Frazzled (dark purple) is localized to the surface of axons (light purple) in the dorsolateral region of the CNS. Hiramoto** ***et al.***[1] **show that Frazzled sequesters secreted Netrin onto these lateral neurons, allowing the trajectory of the dMP2 axon to be precisely redirected.**