of movement is not an issue when the signal starts in the stele — the centre of a root — and moves outwards.

Questions for the future include: which sequences of amino acids in the SHR protein are required for its movement? What limits its movement to one cell layer and not more? And which other proteins participate? Moreover, the vasculature also seems to provide a positional signal in other developmental contexts, such as the differentiation of the surrounding photosynthetic cells in maize leaves[10]. Whether these events also rely on protein movement remains to be seen. ■

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Superconductivity

Up on the C_{60} elevator

Paul Grant

The search for materials that lose electrical resistance — that is, become superconducting — at ever higher temperatures continues to pay dividends.

Organic materials do not naturally make good superconductors — those 'perfect' conductors that lose their electrical resistance completely when cooled below a certain transition temperature, T_C. But given the woefully low T_C values of most metallic superconductors, a lot of work has gone into mining more exotic materials, such as organic compounds, in the hope of finding higher-T_C nuggets. For most of my career, I was one of those diggers. So it is heartening to see Schön, Kloc and Batlogg hit pay dirt with the observation in *Science*[1] of superconductivity at an astounding 117 K in a special form of crystalline carbon. The temperature at which these C_{60} crystals become superconducting is now high enough to begin challenging the existing record for superconductivity, which stands at 164 K and is held by the equally exotic copper oxide compounds.

The first organic materials found to exhibit superconductivity were a series of charge-transfer compounds, discovered in 1979 by Jérome, Bechgaard and colleagues[2], with T_C values of around 1 K. This family, christened the Bechgaard salts, topped out at a T_C of 10–13 K and its superconducting properties were soon forgotten in the excitement that followed the discovery of copper oxide compounds with T_C values above 100 K.

Interest in organic superconductors then waned for half a decade until, in 1991, a T_C of around 18 K was discovered in C_{60} crystals doped with alkali metals, an astonishingly high temperature for an organic-based substance[3]. Because crystalline C_{60} is a natural insulator, it has to be chemically altered to become superconducting. By adding electrons to the empty conduction band, or removing them from the valence band (creating positively charged holes), the crystals become conductors — and, at low enough temperatures, superconductors. This is what doping with alkali metals did.

In the past few years, Batlogg and colleagues have found another way to turn organic materials into superconductors[4–7]. They incorporate the organic compound into the heart of an electronic device called a field-effect transistor (FET), which allows them to inject electrons or holes into the material simply by changing the voltage applied across the transistor. In the case of pure, unadulterated C_{60}, pumping it with electrons transforms it from an insulator into a superconductor with a transition temperature of only 10 K, but doping it with holes raises its transition temperature to a respectable 52 K.

The latest advance by Schön *et al.*[1] builds on their record of 52 K for hole-doped C_{60} by modifying its structure with inert $CHBr_3$ and $CHCl_3$, molecules that expand the crystal lattice in much the same way that alkali metals do. The fact that these particular molecules are inert — they do not donate or accept any electrons — does not matter. The transition temperature of alkali-doped C_{60} increases linearly with lattice spacing, and researchers expected a similar effect with hole-doped C_{60}, except that it was difficult to add holes to C_{60} by chemical means. Schön and colleagues' ability to inject holes using an FET device led to their latest round of experiments.

Here we need a short digression into the theory behind 'conventional' superconductivity, which includes C_{60} but excludes the copper oxides (for which there is no consensus yet). Back in 1957, Bardeen, Cooper and Schrieffer[8] (BCS) showed — in one of the great ironies of condensed-matter physics — that the tiny lattice vibrations (phonons) which cause normal electrical resistance, can, in certain circumstances, bind charge carriers (electrons or holes) into superconducting 'pairs' that flow without resistance.

In the BCS theory, the strength of this charge–phonon pairing, known as λ, is closely linked to the transition temperature, so the greater the value of λ, the higher the T_C. In turn, λ is the product of two other quantities: the number of charges per unit of energy available for pairing, known as the 'density of states', N_0; and the effect of the vibrations of the crystal lattice on the motion of these charges, or, in quantum-mechanical parlance, the 'charge–phonon matrix element', V. One way to increase λ, and thus T_C, is to try to increase N_0 by stretching out the lattice as much as possible so as to pack more mobile charges into a narrower energy range. There is some evidence — perhaps now mostly forgotten — that this effect occurs in the Bechgaard salts.

Schön *et al.*[1] now show that it is possible to 'engineer' the critical properties of C_{60} in a way that is difficult to do in other structures. In most conventional superconductors, N_0 and V are intricately intertwined — in quantum-mechanical parlance, they are based on the same electronic wavefunctions — and it is hard to change N_0 through materials engineering without affecting V. But in solid C_{60} crystals, V is determined by the vibration dynamics of the wavefunctions of the carbon atoms[9], and N_0 by the standing wavefunctions between them. So C_{60} offers a chance to structurally adjust N_0 independently of V.

And that is how Schön *et al.* did it. By expanding the C_{60} lattice with $CHBr_3$, they increased N_0 with little or no apparent effect on V, and achieved a T_C of 117 K. In doing so, they demolished all notions that 'conventional' superconductors would be forever stuck below 50 K.

I have no idea what applications a superconducting C_{60} FET might have. Attempts to use superconducting FETs as power switches have found the device currents to be too small. They are of the order of 1 ampere, whereas conventional semiconductor power can readily handle up to 2,000 amperes at 9,000 volts. The best hope for applications is somehow to reproduce the FET results in a bulk material that is several cubic centimetres in volume, rather than in the nanometre-thick conducting channel of an FET. But let us enjoy this advance in the science of superconductivity for its own sake. It is great to see that we can keep riding the rising elevator of high-temperature superconductivity in organic compounds.

How much higher can T_C go in C_{60}? Schön and colleagues suggest that a further 1% increase in C_{60} separation might result in a T_C of around 150 K. (The existing all-time record for superconductivity is 164 K for copper oxides subjected to extreme pressures.) Any greater expansion of C_{60} would probably destroy its intermolecular bonding completely, but there might be other, more intriguing ways to take advantage of the unique crystal structure of this compound. The separation between the electronic states and vibrational modes of C_{60} exploited by Schön *et al.* is just the sort of thing Little had in mind in the 1960s when he proposed his 'excitonic' model of superconductivity[10]. According to this idea, superconducting paired carriers are glued together by excitons with characteristic energies, unlike the several hundred degrees of phonons, of around 20,000 K — potentially yielding T_C values well above room temperature. Could new excitonic states be introduced by clever chemical or structural modification of C_{60} molecules? Don't step off the elevator just yet. ∎

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Ecology

Crowd trouble for predators

Peter D. Moore

Flocking, herding, swarming: call it what you will. But when you're somebody's lunch there's safety in numbers, even when the predator is an aquatic plant.

Avoiding being eaten is (obviously) one way that most organisms escape premature death. There are many techniques for evading predation, one of the most frequent being the herding or flocking behaviour often seen in certain mammals, birds and fish. But what if the predator happens to be a plant? Does it still help to gather together in groups for mutual support? From work reported by Goran Englund and Sabine Harms (*Oikos* **94**, 175–181; 2001), it seems that it does. Their finding in turn raises such questions as how the prey species (in this case, microscopic aquatic creatures called cladocerans) know when to swarm, and how the swarming mechanism operates.

The plant concerned, the bladderwort *Utricularia vulgaris* (Fig. 1), traps incautious zooplankton within its hollow leaves where it digests them and absorbs their nutrients. Although it is a sedentary predator, bladderwort has an active trapping mechanism, so its carnivory is not entirely passive. Sensory hairs on the outside of the bladder-like leaf detect the local presence of potential prey, resulting in the opening of a trap door and a rush of water and prey into the hollow leaf as negative pressure is released. But being static, the plant must rely on the errant prey organism colliding with the trap. One might predict, therefore, that the higher the density of the zooplankton, the more likely such collisions would become and the more successful the predator would be. Englund and Harms, however, show that at high densities

of cladoceran the number of prey trapped per bladder actually declines.

Observations of the behaviour of the prey, *Polyphemus pediculus*, revealed that they are either randomly or uniformly dispersed at low densities (20 individuals in a 125-ml vessel), whereas at high densities (120 individuals per vessel) they aggregate into swarms. What constitutes the immediate stimulus for this response (such as visual or chemical signals) is unclear, but the flocking behaviour may well be the factor responsible for the reduced success of the predator. Two main changes occur in the swimming behaviour of individual cladocerans when they occur in a swarm — they swim more slowly, and they follow a more contorted path than when they are dispersed.

Obviously, a slower-moving animal is less likely to encounter a static object within a given time, so the chances of a cladoceran hitting a trap are reduced if it slows down. It is also possible that at slower speeds the animal is better able to identify and avoid the traps. Again, it could be argued that a linear motion on the part of the prey is more likely to lead it to traps than random motion. However, given the sensory capacity of the *Polyphemus*, motion may not actually be random, but selective to avoid potentially dangerous objects, such as *Utricularia* leaves.

Another question that requires investigation is the possibility of predator satiation. If the plant has simply had its fill when its prey is abundant, then further increases in prey density would not increase trap success. But in these experiments trap success actually declines as density increases (over a threshold of about 35 animals per 125-ml vessel). Also, the 'handling rate' for a trap — the time it takes for the trapping mechanism to be reset — is around 10–15 minutes, so satiation is not a likely explanation of the observations.

It is of course possible that the swarming behaviour of *Polyphemus* is primarily the outcome of some entirely different behavioural demand. Perhaps it provides better feeding opportunities, or is related to reproductive cycles, or results in more efficient escape from mobile predators. Whatever the reason, swarming still gives the animal a better chance of avoiding consumption by a predatory plant.

Sticking together has proved an effective defence mechanism for many animals subjected to predation, from wildebeest to mackerel. The fact that it works even among microscopic creatures threatened by enemies as passive as a plant may provide insights into the benefits of the swarm. ∎

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Figure 1 **Bladderwort — armed and dangerous (at least to cladocerans).**