

from one end of the material to the other. Measuring the electrical conductivity of materials with different amounts of a conductive filler can provide a measure of this concentration of nanotubes, that is, the percolation threshold. Grunlan *et al.* measured the percolation threshold as an indirect measure of the dispersion. The better dispersed the nanotubes, the easier it should be for them to form a random network and this threshold should then be lower. Indeed, the aggregated, low-pH solid sample had a threshold percolation value ten times greater than that of the dispersed, high-pH value. But the experiment also illustrates some of the complexities involved in nano-engineering materials: at high concentrations of nanotubes, the aggregated sample conducted electrons better. It turns out that dispersing the nanotubes too well places the insulating polymer between the conducting carbon rods, and a higher resistance follows.

It is the elusive yet dramatic enhancement of mechanical properties, and the control of electronic and thermal characteristics, that are ultimately desired in polymer/nanotube composites. Will greater control of nanotube dispersion enable this? Future work should provide the answer. Electrical percolation at the smallest possible nanotube loading is also desirable, but Grunlan and co-workers illustrate that this can be complicated by polymer encapsulation. It also remains to be seen if this colloidal control of the solid can extend to more practical materials such as epoxies. But the authors do succeed in demonstrating that a link between solution and solid material properties can provide an important handle for controlling nanostructure, even for these challenging systems.

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MATERIAL WITNESS

Flat out C₆₀



Graphene has revealed itself from a direction that seems opposite to what one might have expected. First came the zero-dimensional form: C₆₀ and the other fullerenes, nanoscopically finite in every direction. Then came the carbon nanotube, whose one-dimensional form set everyone thinking in terms of fibres and wires. It was just two years ago that the 2D form, graphene itself, appeared: flat sheets of carbon one atom thick (K. S. Novoselov *et al. Science* **306**, 666–669; 2004), which, when stacked in the third dimension, returns us to familiar, lustrous graphite.

It's tempting to wonder if the earlier focus on reduced dimensionality and curvature may have been misplaced. C₆₀ is a fascinating molecule, but useful materials tend to be extended in at least one dimension. Carbon nanotubes can be matted into 'bucky paper', but without exceptional strength. Long, thin, single-molecule transistors are fine, but microelectronics is inherently 2D. Graphene is the master substance of all these, and perhaps, for materials and electronics, sheets were what we needed all along.

You can cut these sheets into device-styled patterns — but that's best done with chemistry (etching with an oxygen plasma, say), as attempts to tear single-layer graphene with a diamond tip are apt to make the tip blunt. (As carbon nanotubes have shown, graphite has a false reputation for weakness.) And graphene is a semi-metal with a tunable charge-carrier density that makes it suitable for the conducting channel of transistors.

But its conductivity is more extraordinary than that. For one thing, the electron transport is ballistic, free from scattering. That recommends graphene for ultrahigh-frequency electronics, as scattering processes limit the switching speeds. More remarkably, the mobile electrons behave as Dirac fermions (K. S. Novoselov *et al. Nature* **438**, 197–200; 2005), which mimic the characteristics of electrons travelling close to the speed of light.

From the perspective of applications, however, one key question is how to make the stuff. Peeling away flakes of graphite with Scotch tape, or just rubbing a piece of graphite on a surface (popularly known as drawing) will produce single-layer films — but neither reliably nor abundantly. Walt de Heer and co-workers have recently flagged up the value of a method several years old, by which silicon carbide heated in a vacuum will decompose to form graphitic films one layer at a time (C. Berger *et al. Science Express* doi:10.1126/science.1125925; 2006).

But maybe wet chemistry will be better still. Graphite was separated into layers nearly 150 years ago by oxidation, producing platelets of water-soluble oxidized graphene, possibly including single sheets. But reducing them triggers aggregation via hydrophobic interactions. This can be prevented by the use of amphiphilic polymers (S. Stankovich *et al. J. Mater. Chem.* **16**, 155–158; 2006). Anchoring bare, single graphene sheets to a surface remains a challenge — but one that may benefit from the wealth of experience of organic chemists.

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