**Graphene: Engineering carbon**

* 03 May 2012 by [**Antonio Castro Neto**](http://www.newscientist.com/search?rbauthors=Antonio+Castro+Neto) and [**Andre Geim**](http://www.newscientist.com/search?rbauthors=Andre+Geim)
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Diamond's glittering hardness is all down to the bonding between carbon atoms within *(Image: Kaj R. Svensson/Science Photo Library)*

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Carbon is a wonder element. Without the amazing stability of its chemical compounds, life on Earth would not be possible. Pure carbon comes in two radically different natural crystalline forms - soft, black graphite and hard, glittering diamond.

Recent decades, however, have seen an explosion of new, engineered forms of carbon. From spherical buckyballs to cylindrical nanotubes, their novel properties have generated much interest and speculation about how they might be exploited. Graphene is just the latest and most exciting example

**The benzene building block**

One hundred and fifty years ago, a 33-year-old chemist called Friedrich August Kekulé was trying to solve a long-standing scientific puzzle: the structure of the benzene molecule. First discovered in the burnt residues of lamp oil by the English chemist and physicist Michael Faraday in 1825, benzene is one of the most important hydrocarbon molecules, both as a basis of organic chemistry and for its broad uses in perfumes and pharmaceuticals.

Benzene was known to consist of six carbon and six hydrogen atoms, but how they fitted together was a mystery. In the 1860s there was no way to determine a molecule's structure directly; it required detective work to piece together the answer from clues such as how the molecule reacted. In benzene's case, no proposed structure explained all of its chemical properties.

Day-dreaming one day, an image of a snake seizing its own tail popped into Kekulé's mind. It was the inspiration he needed: benzene, he realised, was a hexagonal ring of six carbon atoms, with a hydrogen atom dangling from each. Today, this basic hexagonal motif lies at the heart of most carbon-based materials. These include not just organic aromatic molecules such as benzene, but graphite and the plethora of nanoscale forms of the element discovered in recent decades: nanotubes, fullerenes (see "Buckyballs and nanotubes") and graphene. It is the base unit of the new carbon world.

**A question of dimension**

Natural carbon comes in many guises. Two of the most familiar - soot and charcoal - are amorphous collections of carbon atoms and share a characteristic most associated with carbon: they are black. That opacity is also a feature of graphite, one of the two common, pure, crystalline forms of carbon. Graphite, which forms at everyday temperatures and pressures, is a good conductor and supremely soft, well known as the principal component of pencil lead. You would not guess the family connection with carbon's other crystalline form, made at high temperatures and pressures generally deep underground: transparent, insulating and rigid diamond.

The differences lie in how atoms are arranged in the two materials. Carbon atoms have four outer electrons, and in diamond each one is tied up with a neighbour, making for an extremely rigid, three-dimensional structure (see diagram). It is an insulator because no electrons are left over for conduction, and is transparent because light cannot easily excite the tied electrons and thus be absorbed.

Graphite, by contrast, is essentially lots of two-dimensional sheets of hexagonally arranged carbon atoms stacked together. Each atom is connected by strong electron bonds to only three others, leaving spare electrons for conduction and to absorb light. The individual sheets interact with each other only weakly and can slip over neighbouring layers, giving graphite its characteristic softness.

Such are the familiar faces of carbon. But cut it down to the nanoscale [and it begins to take on entirely new dimensions](http://www.newscientist.com/article/mg20427362.000-welcome-to-the-highcarbon-future.html).

**Buckyballs and nanotubes**

The first nanoscale form of carbon to hit the headlines was the buckyball, a near-spherical assembly of 60 carbon atoms arranged in hexagonal and pentagonal rings (see diagram). Its official name is buckminsterfullerene, after the American designer Buckminster Fuller whose geodesic domes it resembles.

The buckyball was first synthesised at Rice University in Houston, Texas, in 1985 through intense laser irradiation of graphite. That achievement earned its discoverers Robert Curl, Harold Kroto and Richard Smalley a [Nobel prize](http://www.newscientist.com/article/mg15220520.700-buckyball-pioneers-score-the-ultimate-goal.html) in chemistry in 1996. It was just the first of a family of similar tiny carbon structures with various numbers of atoms, collectively known as the fullerenes. Fullerenes have since been discovered in natural settings: in pre-Cambrian rocks on Earth, and, in 2010, [in the dusty environment around a white-dwarf star](http://www.newscientist.com/blogs/shortsharpscience/2010/10/buckyballs-abound-in-space.html).

[Carbon nanotubes](http://www.newscientist.com/article/mg15120374.000-through-the-nanotube.html) are not spherical, but cylindrical. Like the fullerenes, they are formed by blasting graphite with lasers, and their walls can be made of single or multiple layers. Controversy surrounds the identity of their discoverer, but they came to worldwide prominence with the work of Japanese physicist Sumio Iijima of the NEC Corporation in the early 1990s. Nanotubes are used to give additional durability to a variety of materials and dyes, but concerns exist about their possible toxicity, for example if inhaled. That, coupled with difficulties in controlling the mechanical and electrical properties of both nanotubes and fullerenes, has put a brake on their wider use.

***Antonio Castro Neto*** *is a professor of physics at Boston University, and director of the Graphene Research Centre at the National University of Singapore*

***Andre Geim*** *is a professor of physics at the University of Manchester, UK. He was co-recipient of the 2010 Nobel prize in physics for his groundbreaking experiments on graphene*