

Graphene – the perfect atomic lattice

A thin flake of ordinary carbon, just one atom thick, lies behind this year's Nobel Prize in Physics. Andre Geim and Konstantin Novoselov have shown that carbon in such a flat form has exceptional properties that originate from the remarkable world of quantum physics.

Graphene is a form of carbon. As a material it is completely new – not only the thinnest ever but also the strongest. As a conductor of electricity it performs as well as copper. As a conductor of heat it outperforms all other known materials. It is almost completely transparent, yet so dense that not even helium, the smallest gas atom, can pass through it.

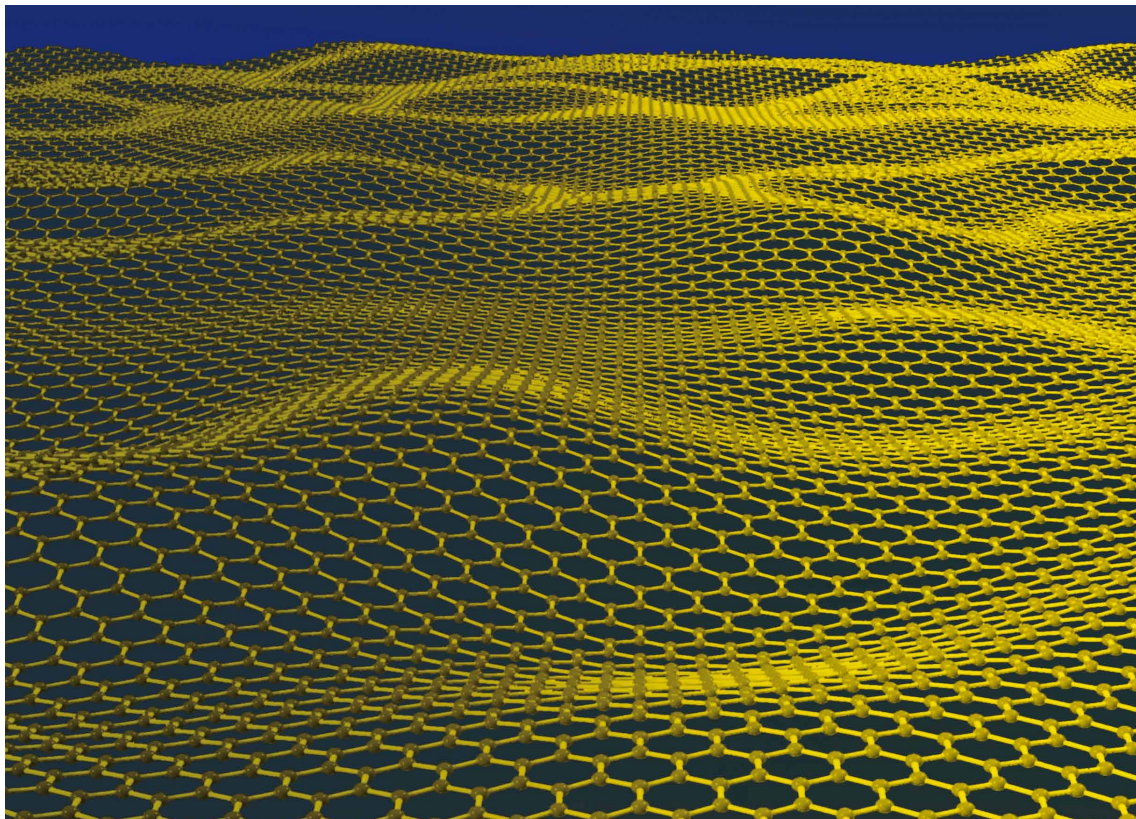


Figure 1. Graphene. The almost perfect web is only one atom thick. It consists of carbon atoms joined together in a hexagonal pattern similar to chicken wire.

Consequently, the article on graphene published in Science in October 2004 stirred up a lot of commotion all around the world. On the one hand, graphene's exotic properties enable scientists to test the theoretical foundations of physics. On the other hand, a vast variety of practical applications now appear to be possible including the creation of new materials and the manufacture of innovative electronics.

Carbon, the basis of all known life on earth, has surprised us once again.

Pencil, paper and sticky tape

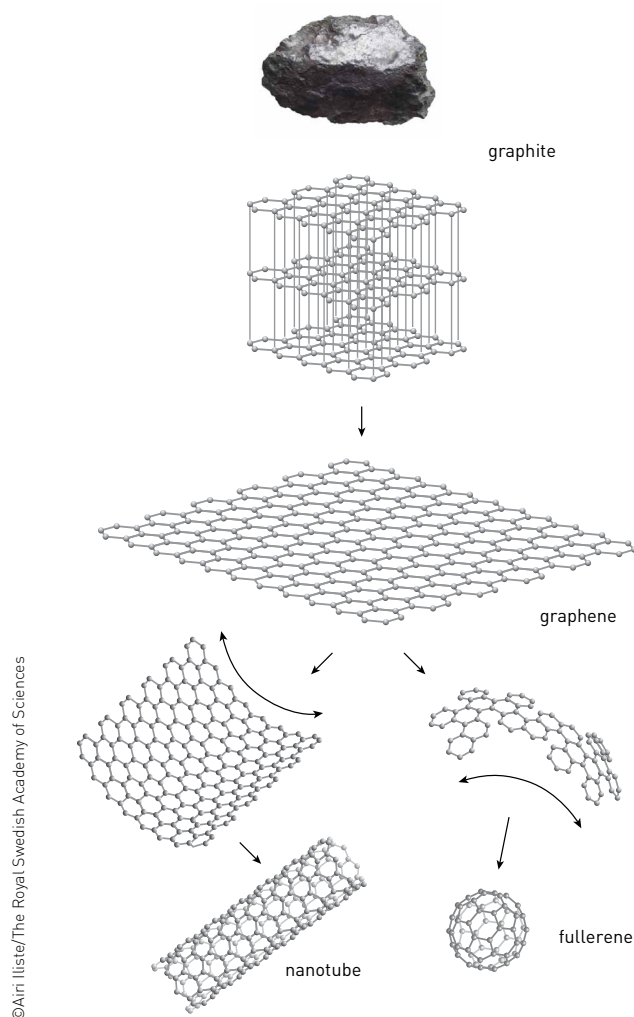
It could not have been easier to obtain graphene, the miraculous material that comes from ordinary graphite such as is found in pencils. However, the most simple and obvious things are often hidden from our view.

Graphene consists of carbon atoms joined together in a flat lattice – similar to a honeycomb structure but just one atom thick. One millimeter of graphite actually consists of three million layers of graphene stacked on top of one another. The layers are weakly held together and are therefore fairly simple to tear off and separate. Anyone who has written something with an ordinary pencil has experienced this, and it is possible, when they did, that only a single layer of atoms, graphene, happened to end up on the paper.

This is what happened when Andre Geim and Konstantin Novoselov used adhesive tape to rip off thin flakes from a larger piece of graphite in a more methodical manner. In the beginning they got flakes consisting of many layers of graphene, but when they repeated the tape-trick ten to twenty times the flakes got thinner and thinner. The next step was to find the minuscule fragments of graphene among the thicker layers of graphite and other carbon scraps. This is when they got their second brilliant idea: in order to be able to see the results of their meticulous work, the scientists from Manchester decided to attach the flakes to a plate of oxidized silicon, the standard working material in the semiconductor industry.

When the plate is placed in a standard microscope one can see a rainbow of colours, similar to what is seen when oil is spilled onto water, and thus determine the number of graphene layers in the flakes. The thickness of the underlying layer of silicon dioxide, was in turn, crucial for revealing the graphene. Under the microscope graph-

ene now came into view – a truly two-dimensional crystalline material that exists at room temperature. Graphene is a perfectly regular network of carbon with only two dimensions, width and length. The basic unit of this pattern consists of six carbon atoms joined together chemically. Graphene, as well as some other forms of carbon that we know of, consists of billions of carbon atoms joined together in a hexagonal pattern.



Waiting for the discovery

Graphene has of course always existed; the crucial thing was to be able to spot it. Similarly, other naturally occurring forms of carbon have appeared before scientists when they viewed them in the right way: first nanotubes and then hollow balls of carbon, fullerenes (Nobel Prize in Chemistry 1996). Trapped inside graphite, graphene was waiting to be released (see fig. 2). No-one really thought that it was possible.

Figure 2. Graphene from graphite. Graphite is a basic material found in nature. When taken apart graphite sheets become graphene. A rolled up layer of graphene forms a carbon nanotube, folded up it becomes a small football, fullerene. Hidden inside graphite, graphene was waiting to be discovered.

Many scientists thought that it would be impossible to isolate such thin materials: they would become crinkled or roll up at room temperature, or even simply completely vanish. In spite of this, some people still tried even though previous attempts to obtain graphene had failed. Formerly, it had been possible to obtain films with a thickness of less than 100 atoms – indeed, some had even been so thin that they were transparent.

One way of obtaining graphene from graphite is to introduce chemical substances between the layers of atoms in order to weaken the bond between them and then subsequently separate the layers. Another method is to simply scratch away the layers of graphite. It was also tried, successfully, to “burn off” the silicon from silicon carbide crystals. At very high temperatures thin layers of carbon were left behind. Different techniques of epitaxial growth, used to create various semiconductor materials, are the most promising as regards producing graphene for use in the electronics industry. Rolls of 70 centimeter wide sheets of graphene are the largest produced so far.



Figure 3. Like a silk sheet. Folded sheets of graphene on a silicon plate. The image was made with a scanning electron microscope, magnified about 5 000 times.

University of Manchester. Science vol 324, 15 May 2009

In a world of paradoxes

Andre Geim and Konstantin Novoselov could only obtain micro flakes of the new material. Despite the minuscule size they could now begin to investigate the two most remarkable traits of graphene, which both influence its electrical properties.

The first is the nearly perfect composition of graphene. The error-free ordering is due to the strong bonding of the carbon atoms. At the same time, the bonds are flexible enough to allow the web to stretch by up to 20% of its original size. The lattice also enables electrons to travel long distances in graphene without disturbance. In normal conductors, electrons often bounce like the ball in a pinball machine. This bouncing weakens the performance of the conductor.

The other unique trait of graphene is that its electrons behave like particles of light, the massless photons, that in a vacuum relentlessly move ahead at a speed of 300 million meters per second. Similarly, electrons travelling in graphene behave as if they did not have any mass and move ahead at a constant speed of one million meters per second. This opens up the possibility of studying certain phenomena more easily on a smaller scale, i.e. without the use of a large particle accelerator.

Graphene also allows scientists to test for some of the more ghost-like quantum effects that so far only have been discussed theoretically. One such phenomenon is a variant of *Klein tunnelling*, which was formulated by the Swedish physicist Oskar Klein in 1929. *The tunnel effect* in quantum physics describes how particles can sometimes pass through a barrier that would normally block them. The larger the barrier the smaller the

chance of quantum particles passing through. However, this does not apply to electrons travelling in graphene – in some circumstances they move ahead as if the barrier did not even exist.

Dream worlds

The possible practical applications for graphene have received much attention. So far, most of them exist only in our fantasies, but many are already being tested, also by Geim and Novoselov themselves.

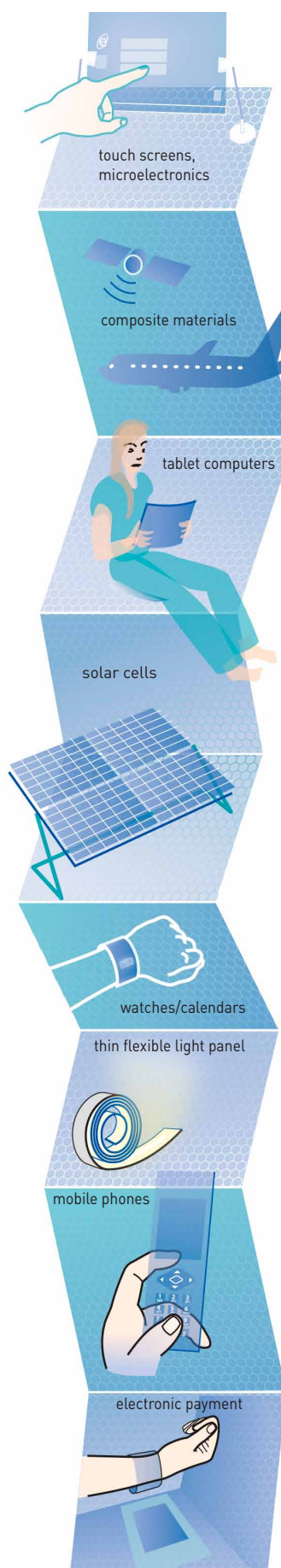
Graphene's conducting ability has spurred a great deal of interest. Graphene transistors are predicted to be substantially faster than those made out of silicon today. In order for computer chips to become faster and more energy efficient they have to be smaller. Silicon hits a size boundary where the material ceases to function. The limit for graphene is even lower, so graphene components could be packed on a chip more tightly than today.

One milestone was passed a few years ago when its key component, a graphene transistor, was presented that was as fast as its silicon counterpart. Maybe we are on the verge of yet another miniaturization of electronics that will lead to computers becoming even more efficient in the future. So far, graphene computers are nothing but a distant dream, although paper-thin transparent computer monitors that can be rolled up and carried in a hand bag have already appeared in commercials for tomorrow's consumer electronics.

In the meantime we can only speculate about some of the more and some of the less realistic applications, all still requiring significant initiatives with their outcomes still being uncertain.

Since graphene is practically transparent (up to nearly 98%) while simultaneously being able to conduct electricity, it would be suitable for the production of transparent touch screens, light panels and maybe even solar cells. Also plastics could be made into electronic conductors if only 1% of graphene were mixed into them. Likewise by mixing in just a fraction of a per mille of graphene, the heat resistance of plastics would increase by 30 °C while at the same time making them more mechanically robust. This resilience could be utilised in new super strong materials, which are also thin, elastic and lightweight. In the future, satellites, airplanes, and cars could be manufactured out of the new composite materials.

The perfect structure of graphene also makes it suitable for the production of extremely sensitive sensors that could register even the smallest levels of pollution. Even a single molecule adsorbed to the graphene surface would be discovered.



A serious game

The list of possible applications for graphene is long. The relentless activity that began following its discovery will eventually most likely bear fruit. No-one can predict what the future might bring, not even this year's Nobel Laureates. They allowed themselves to be led through the labyrinths of chance and had the luck and knowledge to seize opportunities as they appeared – as we all know chance favours only the prepared mind.

Both Laureates think research should be fun. They have been working together for a long time now. Konstantin Novoselov, 36, began working for Andre Geim, 51, as a PhD-student in the Netherlands. He subsequently followed Geim to the United Kingdom. Both of them originally studied and began their careers as physicists in Russia. Now they are both professors at the University of Manchester.

Playfulness is one of their hallmarks. With the building blocks they have at their disposal they attempt to create something new, sometimes even by just allowing their brains to meander aimlessly. One always learns something in the process and, who knows, you may even hit the jackpot. That was the case seven years ago when they created a super sticky tape inspired by the Gecko lizard's ability to stick to even the smoothest surfaces. Prior to that, in 1997, Andre Geim managed to make a frog levitate in a magnetic field; an ingenious way of illustrating the principles of physics. The levitating frog awarded him the Ig nobel prize in 2000 intended to "make people laugh first and think second".

Now, with graphene, Andre Geim and Konstantin Novoselov have written themselves into the annals of science.

LINKS AND FURTHER READING

Additional information on this year's Prizes, including a scientific background article in English, may be found at the website of the Royal Swedish Academy of Sciences, <http://kva.se>, and at <http://nobelprize.org>. The latter also includes web-TV versions of the press conferences at which the awards were announced. Information on exhibitions and activities related to the Nobel Prizes and the Prize in Economic Sciences may be found at www.nobelmuseum.se.

Websites

A. K. Geim's Condensed Matter Physics Group, University of Manchester, www.graphene.org

Kim Group, Columbia University, <http://pico.phys.columbia.edu>

Scientific American, www.scientificamerican.com, search for "graphene"

Lectures (video)

Geim, A. K. *Graphene, Magic of Flat Carbon*, Lancaster University, June 2010,

www.viddler.com/explore/lancsuniscitech/videos/21

Popular scientific articles

Geim, A. K. and Kim, P. (2008) Carbon Wonderland, *Scientific American* 298(4): 90–97,

www.condmat.physics.manchester.ac.uk/pdf/mesoscopic/news/graphene/SciAm_2008.pdf

Chodos, A. (Ed.) (2009) October 22, 2004: Discovery of Graphene, *APS News* 18(9):2,

www.aps.org/publications/apsnews/200910/physics/history.cfm

Original publication

Novoselov, K. S., Geim, A. K., Morozov, S. V., Jiang, D., Zhang, Y., Dubonos, S.V, Grigorieva, I. V. and

Firsov, A. A. (2004) Electric Field Effect in Atomically Thin Carbon Films, *Science* 306(5696): 666–669.

THE LAUREATES

ANDRE GEIM

School of Physics and Astronomy
University of Manchester
Oxford Road
Manchester M13 9PL
UK

www.condmat.physics.manchester.ac.uk/people/academic/geim

Dutch citizen. Born 1958 in Sochi, Russia. Ph.D. 1987 from Institute of Solid State Physics, Russian Academy of Sciences, Chernogolovka, Russia. Director of Manchester Centre for Mesoscience & Nanotechnology, Langworthy Professor of Physics and Royal Society 2010 Anniversary Research Professor, University of Manchester, UK.

KONSTANTIN NOVOSELOV

School of Physics and Astronomy
University of Manchester
Oxford Road
Manchester M13 9PL
UK

www.condmat.physics.manchester.ac.uk/people/academic/novoselov

British and Russian citizen. Born 1974 in Nizhny Tagil, Russia. Ph.D. 2004 from Radboud University Nijmegen, The Netherlands. Professor and Royal Society Research Fellow, University of Manchester, UK.