2010 Nobel Prize

for the discovery of graphene

We all expected this would happen eventually, but it came sooner than expected. Six years after graphene (a single layer of carbon atoms) was first isolated, the two discoverers of this "wonder material" receive a Nobel Prize.

Theorists have written about carbon monolayers since 1947. It was generally believed that such a material could not exist in nature, because the two-dimensional crystalline order would be unstable. The intriguing properties of carbon monolayers (massless electrons and holes at low doping, with a quasi-relativistic dynamics described by the Dirac equation) remained therefore a topic of purely theoretical interest. The calculation of the band structure of a carbon monolayer was the type of problem you gave to students as an elementary application of the tight-binding method, with a *caveat* that this exercise had no physical realization.

▼ The Nobel laureates in a pensive mood. Three countries share in the glory: Both Konstantin Novoselov (right) and Andre Geim are Russian born and educated, but also spent part of their formative years in The Netherlands, before settling down in the United Kingdom. Trivia: Novoselov is the youngest Nobel laureate in Physics since 1973, while Geim is the only Nobel laureate to have also won the Ig Nobel Prize (for levitating a frog). [Photograph courtesy of Manchester University.]

All of this changed in 2004, when Andre Geim and Konstantin Novoselov, with colleagues at Manchester University, showed that carbon monolayers do in fact exist as a stable form of carbon. Their method of fabrication was outside of the beaten path, even a bit idiosyncratic. Instead of the high-level techniques towards the production of few-layer graphite (atomic force microscopy by Philip Kim from Columbia University, epitaxial growth by Walt de Heer from Georgia Tech), Geim and Novoselov used adhesive tape to peal off a single layer from a piece of graphite. It should not work, but it did. As Kim graciously admits in his public lectures: "We were scooped by a piece of Scotch tape".

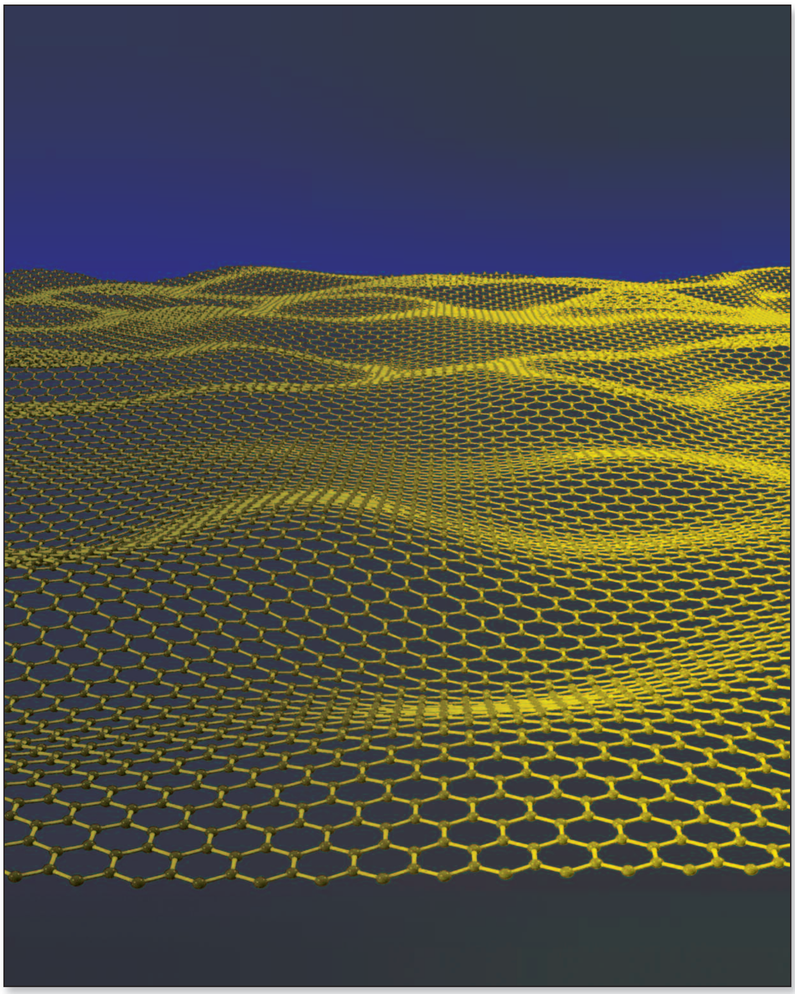
The single layer flakes are very rare in the debris of graphite flakes, typically there are just a few μm^2 size monolayers scattered randomly in a cm^2 area. Searching for the monolayers is therefore quite like trying to find a needle in a haystack. This explains why earlier attempts (notably by Rodney Ruoff from Washington University) to find monolayers using probes with atomic resolution had failed. The optical detection of monolayers was the key innovation of the Manchester group that made the discovery of graphene possible. Graphene flakes can be located among the multilayers on a silicon substrate because of their slightly different colour under an optical microscope. Once located, atomic force microscopy could verify that these flakes were indeed monolayers. While atomic force microscopy can count the number of layers in the flake and is sufficient to demonstrate that a monolayer has been isolated, to actually confirm 2D electron dynamics one needs to observe the quantum Hall effect. That successful confirmation was reported in 2005 by the Manchester group. Kim and his group could provide an independent confirmation, after they had switched to the adhesive tape method of fabrication. This method has now been adopted by laboratories all over the world, and has produced a wealth of new phenomena involving electronic, optical, mechanical, and chemical properties. This is my list of favorite breakthroughs (incomplete and biased by my own interests):

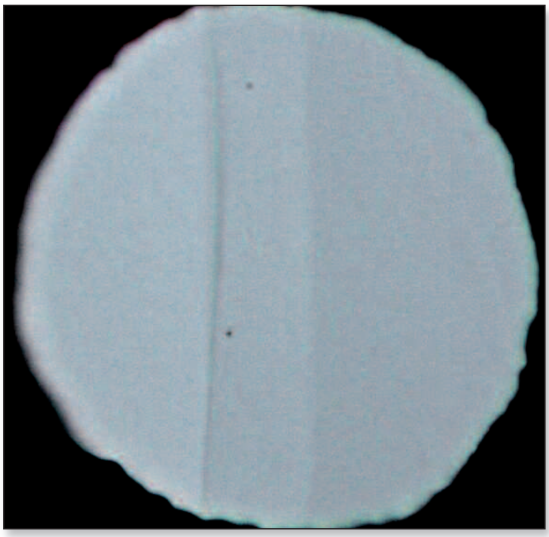
- *Graphene is the first two-dimensional crystal.* While strictly 2D crystalline order is unstable due to thermal fluctuations, graphene can exist as a stable sheet of carbon atoms with relatively weak ripples and few crystal defects. Before 2004, atomic monolayers of carbon were only known to exist in the rolled-up form of nanotubes or fullerenes. In graphite, 2D layers exist but not in isolation. The coupling between the layers in graphite is relatively weak compared to the carbon-carbon bond within the layers, and yet this weak coupling destroys the special properties of 2D motion. In particular, the zero-mass property of the conduction electrons is unique for the single layer – it is lost in the double layer.
- *Graphene is representative of a whole class of two-dimensional crystals.* The "Scotch tape" method invented by the Manchester group to isolate

graphene (mechanical exfoliation followed by optical detection), can be used to extract atomic monolayers from a variety of strongly layered materials. That these monolayers are stable in air at room temperature, without the protection offered by a 3D structure, was completely unexpected.

- *Graphene exhibits two-dimensional dynamics at room temperature.* Before the discovery of graphene, 2D electron dynamics was studied extensively in semiconductor heterojunctions. Low temperatures (a few Kelvin) are needed for these experiments, because the dynamics is no longer two-dimensional at higher temperatures. Graphene remains strictly 2D at room temperature, retaining its structural stability and good conductivity. A striking demonstration of 2D dynamics at room temperature was the observation of the quantum Hall effect at 300 K.
- *Graphene has massless carriers of electrical current.* The periodic potential of the carbon atoms, arranged on a honeycomb lattice, has a unique effect on the electron dynamics: the effective mass tends to zero at low energies. This surprising property of a carbon monolayer goes back to its first theoretical study in 1947 by Philip Wallace (1915–2006), and it plays a role in the 1D motion in carbon nanotubes. But the most striking consequences of massless dynamics require two spatial dimensions, and they remained of purely theoretical interest before the discovery of graphene.

▼ **FIG. 1:** Artists impression of a carbon monolayer, based on data obtained by transmission electron microscopy of a freely suspended graphene sheet. The ripples have a typical height of 1 nanometer and width of 25 nanometer. [Illustration by Jannik Meyer, Ulm.]





▲ **FIG. 2:** The eye can see the difference between a single layer of carbon atoms (central strip) and two layers (region to the right). Each atomic layer absorbs 2.3 percent of incident light, determined by the fine structure constant. [Photograph by Rahul Nair, Manchester.]

Practical applications of graphene are likely to follow. Geim expects that “it has all the potential to change your life in the same way that plastics did”. It is too early to decide at this stage whether or not graphene will fulfill this promise of “wonder material”. However, the importance of Geim and Novoselov's pioneering work for fundamental physics is already quite evident. More than half a century of theoretical studies of a system which was not believed to exist, have now found a realization in nature. ■

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About the author

Carlo Beenakker is a condensed matter theorist at the Lorentz Institute of Leiden University, The Netherlands. He is the recipient of an ERC Advanced Investigator award for the study of graphene.

More about graphene

Can be found in the feature “Graphene, new physics in two dimensions” by N.M.R. Peres in *Europhysics News* **40/3**, 17 (2010).