The rise and rise of graphene

This year's Nobel Prize in Physics can be seen as part of the larger story of hexagonally bonded carbon.

The recent award of the Nobel Prize in Physics to Andrei Geim and Konstantin Novoselov, two Russian-born physicists working at Manchester University in the United Kingdom, "for groundbreaking experiments regarding the two-dimensional material graphene", is notable not just because it comes only six years after they and six others published their breakthrough paper in *Science*[1], or because Novoselov is among the prize's youngest-ever winners (he is just 36). It is also notable because, together with the 1996 Nobel Prize in Chemistry (awarded for the discovery of fullerenes) and the 2008 Kavli Prize in Nanoscience (for carbon nanotubes), it completes a trifecta of mega-awards to three different topologies of what is otherwise exactly the same substance: hexagonally bonded carbon.

Although the Nobel committee remarked that "carbon, the basis of all known life on earth, has surprised us once again"[2], the 2010 prize continues a single narrative: the ongoing discovery of what a few sheets of sp^2-hybridized carbon atoms can do. Indeed, many of today's leading graphene researchers are former or present nanotube researchers (although Geim and Novoselov are not), and many of the proposed applications of these materials are similar. Publication volumes on fullerenes, nanotubes and graphene taken together have been growing at a constant exponential rate since 1998, doubling every five years, which suggests that they are in some sense a single community.

The changing tenor of the rationales for the three prizes (as revealed in press releases and other documents published by the prize-awarding bodies) reflects the development and maturing of research into hexagonally bonded carbon. The press release about Harry Kroto, Richard Smalley and Robert Curl sharing the 1996 Nobel Prize in Chemistry noted that, 11 years after the discovery, "no practically useful applications have yet been produced"[3]. And only 30 fullerene-related patent applications were filed from 1985 to 1991 according to Google patents, with few or none of these translating to commerical success. However, this should not detract from the fact that the fullerenes have had a widespread impact throughout science[4].

Carbon nanotubes were discovered in 1991, and the number of related patent applications filed by 1997 was about 90 — triple the number for fullerenes in the corresponding period. By the time Sumio Iijima shared the Kavli Prize for Nanoscience in 2008 for this discovery, nanotubes were being manufactured in the hundreds of tons per annum or more by major companies such as Bayer and Showa Denko[5], and potential applications featured prominently in the citation for the prize[6].

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Of the three prizes, however, it is the 2010 Nobel Prize in Physics that arrives with the most extensive and detailed discussion of applications, complete with cartoon drawings of futuristic personal electronics[2]. There have also been about 165 patent applications involving graphene since 2004 (although Geim himself did not file one[7]), with correspondingly high manufacturing volumes[5]. The proposed applications, however, are quite familiar: transistors, touch screens, solar panels, composite materials and so on[2,8].

This relatively early maturity relies in part on work that had been previously done on fullerenes and nanotubes. But graphene does have intrinsic advantages: it is easier to pattern than nanotubes, it doesn't come with an uncontrolled chirality and it is easier to observe. Similarly, it can be argued that micrometre-long nanotubes are easier to work with than individual fullerenes. This transition is neatly reflected in the types of microscopy used in the prize-winning work for each material. Graphene can be observed, and its layer-number counted, under an optical microscope — a realization that was key to the 2010 prize. Nanotubes, on the other hand, were discovered using an electron microscope, and electron microscopy remains among the most common means of observing them today. And the original fullerene paper did not have an image of the molecule at all, relying instead on mass spectrometry and calculations to argue in favour of the famous spherical structure[9,10].

The physics seems to get richer, too, as the dimensionality increases from zero, to one, to two. "The hype is bigger," Carlo Beenakker told the *New York Times* in 2007, "because the physics is richer"[11]. Perhaps not surprisingly, Geim agrees: "it's two-dimensional, which is the best possible number for studying fundamental physics"[7]. Massless electrons and an anomalous quantum Hall effect are both unique to graphene and have been much studied by the Manchester group and others, notably at Georgia Tech and Columbia. Graphene is also an excellent platform for observing otherwise inaccessible phenomena such as the Klein paradox. Future challenges include explaining the value of the minimum conductivity of graphene, exploiting the valley degrees of freedom (a field known as 'valleytronics') and exploring the potential for superconductivity in graphene.

There are also practical obstacles that must be overcome before graphene can fulfil its potential for applications. Key among these is achieving control over the energy bandgap, which is zero for large-area single-layer graphene: this is a major problem in electronics because it prevents transistors from switching off[12]. Advances in manufacturability are also needed. Even at the present stage of development, however, graphene is already being incorporated into products in industrial labs, and we will probably see it joining carbon nanotubes in a variety of real products in the near future as the story of carbon continues to unfold. ❐

References

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