AUTHOR COMMENTARIES - 2008

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U. Manchester's Andre Geim: Sticking with Graphene—For Now

The *Science Watch*® (Print Version) Newsletter Interview

Grahene is one atom thick, which makes it the thinnest material in the universe, or at least tied for the thinnest should some novel competitor be lurking out there somewhere, as yet undiscovered. It’s a crystal arranged in a chicken-wire or honeycomb lattice, and a very high-quality crystal at that. According to its creator, the University of Manchester solid-state physicist Andre Geim, no one has yet found a single vacancy or dislocation in a graphene crystal made by following his recipe. Graphene is also highly conductive, conducting both heat and electricity better than any other material, and it is strong. Stronger than diamond, if you could imagine a diamond as thin as graphene.

Ever since Geim published his first paper on graphene in *Science* in October, 2004—"Electric field effect in atomically thin carbon films"—the two-dimensional variation on graphite has taken materials science and condensed-matter physics by storm, while launching Geim into prominence among Thomson Reuters’ measures of hot researchers in the field. Geim’s 2004 *Science* paper has now been cited nearly 600 times (see adjoining table), eclipsed only by a November, 2005 article in *Nature* on the unique quantum mechanical properties of these materials, "Two-dimensional gas of massless Dirac fermions in graphene," which has been cited roughly 650 times. Beginning in early 2007, this paper spent more than a year on the upper rungs of the *Science Watch*® Physics Top Ten.

More recently, the latest bimonthly file of the Hot Papers Database shows that seven reports from Geim and colleagues published in the last two years are currently being cited at a notably high rate compared to papers of similar type and age.

Geim's research has wielded impact beyond the physics world. In 2007, for example, one of his previous reports, discussing his work on "gecko tape"—a microfabricated adhesive that mimics the super-sticky action of the gecko lizard's footpads—was identified as a core paper in a Thomson Reuters Research Front in the field of Microbiology.

Geim is also known for injecting, quite literally, a bit of levity into science, with the 1997 experimental levitation of a frog by means of a magnetic field. The work earned Geim a share of one of the tongue-in-cheek IgNobel Awards in 2000, while also entertainingly demonstrating valid principles of diamagnetism.

Geim, 49, received his Master's in Science degree in 1982 from the Moscow Physical-Technical University and his Ph.D, five years later, from the Institute of Solid State physics in Chernogolovka, Russia. After spending two years as a research scientist at the nearby Institute for Microelectronics Technology, Geim left for the West to become a visiting fellow at Nottingham University in the U.K. He led a peripatetic career through 1994, when he became an associate professor at the University of Nijmegen in the Netherlands. In 2001, he became a professor of physics at England's University of Manchester, where he is also director of the Centre for Mesoscience & Nanotechnology. In 2007 he was elected a Fellow of the Royal Society.

"We've never known materials like this before, in fact, it was assumed that they couldn't exist."

Geim spoke to *Science Watch* from his Manchester office.

SW: Graphene seems to be just one particularly extraordinary example of a long line of unique discoveries in your research. How would you characterize your research style?

It is rather unusual, I have to say. I do not dig deep—I graze shallow. So ever since I was a postdoc, I would go into a different subject every five years or so. Every time I took a different university position, I would change subjects. I don't want to carry on studying the same thing from cradle to grave. Sometimes I joke that I am not interested in doing re-search, only search. There have been a few hits, like graphene and levitating frogs and gecko tape. When I moved from Holland to the University of Manchester, it was a good time to try new subjects, and one of the things that came out of it was gecko tape and another was graphene, and a third involved domain walls in magnetic structures. Graphene certainly turned out to be the biggest hit, scientifically the most important. Even though gecko tape is very popular these days, we had to completely abandon it. Graphene turned out to be much, much more important than anything else.

SW: Is there a common theme to your research strategies?

The common theme is to use experimental facilities that are available and to see what we can do—what other people haven't done previously. I'm looking for an unexplored area of research, based on a combination of knowledge and facilities. I'm not trying to reach some theoretical goal set forth by someone else. It's like this kids' toy, Lego. You have all these different pieces, cubes and stuff, and you have to build something based strictly on what pieces you've got. So in research, some of the Lego pieces are facilities, some are random knowledge, and we try to build up something new from that. I guess we could call it the "Lego Doctrine."

SW: So how did this Lego Doctrine lead you to graphene?

We had facilities to study small samples. I have knowledge from low-dimensional systems that I had worked on during my postdoctoral studies. The third element here was what I jokingly call scientific spite: I looked at the carbon-nanotube community and was spiteful about how many nice results they had. I thought that I could do something like carbon nanotubes but from a different perspective. Why couldn't we do carbon nanotubes, but unfolded? That was the initial idea: try to do something similar to carbon nanotubes, but do it by starting with graphite and then polishing the graphite down to a few layers thick, or at least whatever we could reach. At that time, neither I nor anyone else thought it was possible to reach a single layer, but 10 or 100 layers seemed quite reasonable. So that was the goal: make 100-layer graphite and try to study it, hoping to address problems similar to those in the carbon-nanotube world. And we started this about five years ago, 2002 to 2003.

SW: So you literally polish the graphite down until it's one layer thick?

Let me tell you a nice story: I had a new Chinese Ph.D. student. I bought a big piece of highly oriented pyralytic graphite, known as HOPG, and I asked him to make films as thin as possible. Initially I gave him a very fancy polishing machine. A piece of Lego was in place, see. Three weeks later, he comes back and says he's succeeded. He shows me a Petri dish with a tiny speck of graphite at the bottom. I look in the microscope and see that it's about 10 microns thick—maybe 1,000 layers. I ask him, "Can you polish it a little bit more?" And he says he would need another piece of HOPG, which costs about $300. I must say that I was not very polite when explaining to him that you don't have to polish off a whole brick to get a grain of it. His equally polite reply was, "If you're so clever, try to do it yourself."

This was a point of no return. I decided to use Scotch tape. Graphite is a very layered material. It's like mica. It splits into planes very easily. So you put Scotch tape on graphite or mica and peel the top layer. There are flakes of graphite that come off on your tape. Then you fold the tape in half and stick it to the flakes on top and split them again. And you repeat this procedure 10 or 20 times. Each time, the flakes split into thinner and thinner flakes. At the end you're left with very thin flakes attached to your tape. You dissolve the tape and everything goes into solution. It turned out—and no one would have guessed—that the thin flakes did not lump and scroll. Within a week we had a working device. It wasn't graphene. It was still graphite—maybe 10 layers thick—but we had gone farther than anyone else in this direction, and we started to make transistors from it.

SW: Scotch tape?

Yes. It's now called the "Scotch tape technique." I fought against this name, but lost. It doesn't sound very high-tech, does it? Then again, you could equally call the way nanotubes are grown a "barbeque technique." Nanotubes and all sorts of fullerenes can be found in soot at the bottom of a barbeque tray. There are now more sophisticated ways of getting graphene, but Scotch tape gave us the first glimpse of what's possible—that you can essentially pull a single atomic plane off of graphite.

SW: What's the difference between graphite and graphene?

Graphene is a single atomic plane of graphite. Graphite is a stack of graphene planes. It's very important to emphasize that all matter, all materials we knew before this, were and are three-dimensional materials. Even those that were called one- or two-dimensional were never actually one or two. Take carbon nanotubes. People might refer to them as one-dimensional, but if you look carefully, you see that a nanotube is a cylinder—thin and long but still a three-dimensional object. Here, for the first time ever, we really are dealing with strictly two-dimensional matter. We've never known materials like this before. In fact, it was assumed that they couldn't exist.

SW: What were the arguments against 2-D materials?

There are very powerful theoretical arguments that 2-D materials cannot be grown, because whenever you try to grow something of dimensionality less than three in our three-dimensional world, it will morph and go through all sorts of three-dimensional structures. We fooled nature by making first a three-dimensional material, which is graphite, and then pulling an individual layer out of it. This way is not forbidden by theory.

SW: You've said these graphene sheets are revealing secrets of fundamental physics. Can you tell us more about this?

If graphene were just the thinnest material and so on, I would not be giving this interview. It's an extraordinary system and provides a cornucopia of new physics. The most important physics comes from the very unusual electronic properties of this material. The point is that in all material we knew about until graphene came along, charge carriers could be described classically as bullets or billiard balls moving through the material, or quantum mechanically as these electron waves described by the wave equation of quantum physics, the Schrödinger equation. In graphene, conducting electrons arrange themselves into new types of quasi-particles, or new types of waves, if you wish, which move according to the laws of relativistic quantum physics—the Dirac equation. They behave like neutrinos or electrons moving at close to the speed of light. I like to emphasize that they are not really relativistic; they just mimic these relativistic laws. That's a new kind of thing to study. It's like the Large Hadron Collider, but on your desktop.

Highly Cited Papers by Andre K. Geim and Colleagues, Published Since 2004
(Ranked by total citations)

Rank	Paper	Cites
1	K.S. Novoselov, *et al.*, "Two-dimensional gas of massless Direc fermions in graphene," *Nature*, 438 (7065): 197-200, 2005.	643
2	K.S. Novoselov, *et al.*, "Electric field effect in atomically thin carbon films," *Science*, 306 (5296): 666-9, 2004.	570
3	A.K. Geim, K. S. Novoselov, "The rise of graphene," *Nature Materials*, 6(3): 183-91, 2007.	224
4	K.S. Novoselov, *et al.*, "Two-dimensional atomic crystals," *PNAS*, 102 (30): 10451-3, 2005.	166
5	K.S. Novoselov, *et al.*, "Unconventional quantum Hall effect and Berry's phase of 2p bilayer graphene," *Nature Physics*, 2(3): 177-80, 2006.	148

SOURCE: Thomson Reuters Web of Science®

SW: What technological applications do you foresee for graphene, and are we going to need new technologies to create it to make these applications viable?

Well, there is another way of producing graphene, and it's called epitaxial growth. You can essentially grow a single layer on top of other crystals. If you find a crystal with a matching substrate, you can grow graphene on top of this substrate, too. It's been shown that this can be done on silicon carbide, iridium, nickel, and other materials. Many applications, especially in electronics, require graphene wafers and are hard to imagine without epitaxial growth.

As for what those applications are, the idea is to consider graphene as unfolded carbon nanotubes. Whatever people have suggested for carbon nanotubes can then be done with graphene. I have to say, though, that I'm always very skeptical about applications. When someone asks about applications in my talks, I usually tell a story about how I was on a boat one day watching dolphins, and they were jumping out of the water, allowing people to nearly touch them. Everyone was mesmerized by these magnificent creatures. It was an extraordinary romantic moment—well, until a little boy shouted out, "Mom, can we eat them?" It's a similar matter here—as in, okay, we just found this extraordinary material, so we're enjoying this romantic moment, and now people are asking if we can eat it or not. Probably we can, but you have to step back and enjoy the moment first.

SW: So what are the applications? How do you serve up graphene?

If you insist on going in this direction, we can talk about the realistic applications, and then about the dreams that might someday come true. In realistic applications, people have now learned how to make graphene suspensions, not too dissimilar to dissolving Scotch tape but on an industrial scale. You use this suspension as a filler in plastic to make composite materials—conductive plastics that might not be as strong as graphene itself but are strong enough. Several groups also used graphene suspension to make a conductive, transparent film. So you have glass. You spin your suspension over this glass and you make optically transparent and conductive films. These are used, of course, in many, many applications. The easiest one is right in front of you, your LCD screen, and graphene looks very promising for this kind of application.

An example of a graphene dream could be what I call "Graphenium Inside," like "Pentium Inside." We're about to reach the point where silicon can't be miniaturized any further; the material itself becomes unstable at sizes down to 10 nanometers. People are looking for a material to substitute, to take over from silicon and go to smaller sizes. There have been about ten candidates in the last ten years and all, in my opinion, have failed miserably. Graphene is a strong possibility as a substitute. This material is not great for computer chips with large transistors, but as you decrease in size, it becomes far stronger. Every big-name company, from Intel to IBM to Samsung, now has its fingers in this particular pie, but it's still a dream at the moment, not a realistic application.

You said your research style is to graze and find a new field every five years. You published your discovery of graphene in 2004. Are you planning on leaving the field next year?

No, although I'm often asked that question by my colleagues who, I believe, hope I'll leave the field to them. No chance, guys! You'll have to cope with my sarcastic jokes for longer. With graphene, each year brings a new result, a new sub-area of research that opens up and sparks a gold rush. I want to put many more stakes in the ground before it's covered completely, before all the interesting science is claimed and taken. Then it will be time to move on.

Related information:

Read two Fast Moving Front commentary features from Andre Geim. The first is regarding his *Science* paper published in October, 2004 titled, "Electric field effect in atomically thin carbon films." The second is in regards to his *Nature Materials* paper published in July, 2003 titled, "Microfabricated adhesive mimicking gecko foot-hair." This commentary includes an image of imetic gecko hairs seen in a scanning electron microscope.

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