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October 22, 2004: Discovery of Graphene



Scientists often find ingenious ways to attain their research objectives, even if that objective is a truly two-dimensional material that many physicists felt could not be grown. In 2003, one ingenious physicist took a block of graphite, some Scotch tape and a lot of patience and persistence and produced a magnificent new wonder material that is a million times thinner than paper, stronger than diamond, more conductive than copper. It is called graphene, and it took the physics community by storm when the first paper appeared the following year.

The man who first discovered graphene, along with his colleague, Kostya Novoselov, is Andre Geim. Geim studied at the Moscow Physical-technical University and earned his PhD from the Institute of Solid State Physics in Chernogolovka, Russia. He spent two years at the Institute for Microelectronics Technology before taking a fellowship at Nottingham University in England. In 1994, he joined the faculty at the University of Nijmegen in the Netherlands, moving back to England's University of Manchester in 2001 to become director of the Centre for Mesoscience and Nanotechnology.

Geim has a knack for quirky yet significant research subjects. He made headlines in 1997 when he used a magnetic field to levitate a frog, garnering him an Ig Nobel Prize in 2000. He once co-authored a paper with his favorite hamster, "Detection of earth rotation with a diamagnetically levitating gyroscope," insisting that "H. A. M. S. ter Tisha" contributed to the levitation experiment "most directly." (According to Wikipedia the hamster later applied for a PhD at the University of Nijmegen.) And in 2007 his laboratory developed a microfabricated adhesive mimicking a gecko lizard's sticky footpads.

Geim has said that his predominant research strategy is to use whatever research facilities are available to him and try to do something new with the equipment at hand. He calls this his "Lego doctrine": "You have all these different pieces and you have to build something based strictly on the pieces you've got." In the case of graphene, his lab was well-equipped for the study of small samples.

Carbon nanotubes were–and are–a major area of materials research, and Geim thought it might be possible to do something similar to carbon nanotubes, only in an unfolded configuration. He had the idea to polish down a graphite block to just 10 or 100 layers thick and then study the material's properties. One of his students was assigned the task, and produced a speck of graphite roughly 1000 layers thick–a little short of the mark.

That is when Geim had the idea to use Scotch tape to peel away the top layer. Flakes of graphite come off onto the tape, and the process can be repeated several times to achieve progressively thinner flakes attached to the tape. He then dissolved the tape in solution, leaving him with ultra-thin flakes of graphite: just 10 layers thick. Within weeks, his team had begun fabricating rudimentary transistors with the material. Subsequent refinements of the technique finally yielded the first graphene sheets. "We fooled nature by first making a three-dimensional material, which is graphite, and then pulling an individual layer out of it," said Geim.

In October 2004, Geim published a paper announcing the achievement of graphene sheets in *Science* magazine, entitled "Electric field effect in atomically thin carbon films." It is now one of the most highly cited papers in materials physics, and by 2005, researchers had succeeded in isolating graphene sheets. Graphene is a mere one atom thick– perhaps the thinnest material in the universe–and forms a high-quality crystal lattice, with no vacancies or dislocations in the structure. This structure gives it intriguing properties, and yielded surprising new physics.

From a fundamental standpoint, graphene's most exciting capability is the fact that its conducting electrons arrange themselves into quasi-particles that behave more like neutrinos or electrons moving close to the speed of light, mimicking relativistic laws of physics. In most materials, charge carriers behave in a more classical fashion. Geim has compared the effect to the Large Hadron Collider, "but on your desktop." This makes it possible to test certain ideas in particle physics and astrophysics conceptually on a smaller tabletop scale, rather than in a multi-million dollar collider.

The most obvious application is using graphene to replace silicon chips, since that technology is fast reaching its fundamental limits (below 10 nanometers). It is also possible to make graphene using epitaxial growth techniques–growing a single layer on top of crystals with a matching substrate–in order to create graphene wafers for electronics applications. So graphene holds promise for use in high-frequency transistors in the terahertz regime, or to build miniature printed circuit boards at the nanoscale. There are technical barriers: graphene is metallic, so scientists would need to devise a way to make the material semiconducting. They will also need to develop a technique for producing graphene sheets in large quantities if the material is to find application in large-scale industrial sectors.

For now, graphene is being explored as a filler in plastic to make composite materials, in much the same way that carbon nanotubes are used to bolster the strength of concrete materials, for example. Graphene suspensions can also be used to make optically transparent and conductive films suitable for LCD screens.