Graphene: The Future of Electronics Lies in Quantum Theory

Could solving the problems of theoretical physics, seemingly distant from reality, influence our daily life? The story of graphene, already called the wonder material, suggests that the answer is *Yes*.

Let's consider one of the most relevant elements to human life, carbon. The best-known allotropes of carbon are diamond and graphite. Graphite, which is the more commonly found form, consists of separate layers, each only one atom thick, which have a honeycomb-like structure. These layers are relatively weakly bound to each other and separate easily — a property that makes writing possible, pencil-lead simply transferring to paper. In fact, graphite gets its name from the Greek word γράφω, which means *to write*. In 1984, Gordon W. Semenoff showed that electrons in a single layer of graphite are described by the Dirac equation in its simplest form, valid for particles in a two-dimensional world that have no mass. Isolating a single layer of graphite (later called graphene), however, seemed a remote possibility at that time. A breakthrough in our knowledge of different forms of carbon followed soon enough in the form of fullerenes (1985) and nanotubes (1990). But it took another 15 years to rid ourselves of the dogma that such a truly two-dimensional system cannot exist in our world. Finally, in 2004, Andre Geim and Konstantin Novoselov from the University of Manchester succeeded in producing the first isolated graphene flakes.

The contribution of Geim and Novoselov to condensed matter physics, honored with the Noble Prize in 2010, goes far beyond the discovery of a very interesting material; what is potentially much more important is their attempt to change the prevailing dogma in many fields of science. The scientists decided to publicize the method of isolating graphene, giving full details of the process using instructional videos and organizing training courses for members of competing teams. Thus, research on graphene was undertaken immediately by a few dozen teams from around the world, leading to unprecedented explosion of publications and citations related to the material. The theoretically predicted properties of the new material were soon confirmed experimentally; the two most interesting among them seem to be electrical conductivity and visible light absorption, two properties that can be expressed solely in terms of the fundamental constants of nature: the electron charge, the speed of light in vacuum, and the Planck constant. More interestingly, the relatively large conductance of the monolayer is accompanied by the absorption of light in very small quantity (about 2%), making graphene a promising building block for electrical circuits in LCD screens and in e-paper.

In 2005, Geim and Novoselov together with colleagues from Russia and the Netherlands published a paper in *Nature* describing a field-effect transistor built entirely from graphene, which makes it possible to change the concentration of charge carriers smoothly by applying an external electric field — and even to fully replace electrons with holes — and vice versa. Such a device has no counterpart in silicon-based electronics. Recently, researchers at IBM achieved two major successes in fabrication of devices entirely build of graphene: in February 2010, transistors with an on and off rate of 100 gigahertz (far exceeding the rates of previous attempts) were created. Next, in June 2011, the first graphene-based integrated circuit (a broadband radio mixer) was built. These achievements show that graphene electronic nanodevices can conceivably replace silicon ones.

It is quantum mechanics that gives graphene its superlative properties: one of its four electrons in the outermost shell is relativistic, and due to quantum mechanics doesn't know if it is up or down because of uncertainty, and this characteristic is responsible for its outstanding electrical and thermal conductivity as well as transparency. Among the diverse applications of graphene currently being considered, those related to *spintronics* are the most advanced. In contrast to classical electronics, which operate on the electron charge and are slowly approaching the limits set by quantum mechanics (going by the famous Moore's Law, the development in chip performance will come to an end by 2025 or so), spintronics focus on a different property of the electron: the so-called *spin* (or the magnetic moment). To turn around a spin requires much less energy than charge translation; therefore, the fundamental constraints to the development of spintronics lie far beyond those that apply to classical electronics.

Graphene is a particularly convenient material for spintronic applications because of its high level of quantum coherence: an electron injected into graphene by an external electrode made of a ferromagnetic metal retains its identity and spin orientation for a very long time. Moreover, electrons in graphene have an additional quantum number (*valley index*), and the same operations can be performed on them as those performed on the spin. Electronics that make use of the valleys in graphene (called *valleytronics*) seem attractive because valley information is extremely robust against scattering from lattice defects, external potentials, etc. Several versions of valleytronics were discussed theoretically: In 2007, a Polish-Dutch team of researchers from the universities of Jagiellonian, Warsaw, and Leiden proposed to build a valley filter using a constriction with zigzag edges. In 2010, physicists from the University of Konstanz pointed out that the so-called Rabi oscillations between quantum states belonging to different valleys may appear in carbon nanotube quantum dots. In April 2011, scientists from the Naval Research Laboratory in Washington showed that a line defect may lead to nonequilibrium valley polarization even in bulk graphene without the necessity of confining an electron.

The discovery of graphene has led to the development of other materials, such as molybdenum sulfide or boron nitride, that are just one atom thin. These materials can be combined to produce specific properties for specific applications. It is difficult to name right now the materials and phenomena discussed here that will find large-scale applications in future electronics; it is possible that some totally different materials, unknown today, will upstage these materials. What is certain, however, is that the nearly hundred-year-old mathematical tools provided by the quantum theory will play a key role in the design of materials and the future of electronics.

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