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The Amazing Miracle Material: Graphene

A piece of graphene aerogel—weighing only 0.16 mg per cubic centimeter—resting on grass spikes.

Credit: Long Wei/EPA

Graphite, the shiny grey stuff in your pencil, has unexpected powers.

When you write with it, you're scraping off a *very* thin layer. For decades, scientists tried to slice a layer just one atom thick—which they called *graphene*.

But it was only 13 years ago, at the University of Manchester, that they succeeded. Graphene turned out to be far more miraculous than they could have ever imagined.

It's the thinnest compound known to man, thousands of times thinner than the human hair. It's also the lightest, a thousand times less dense than paper.

Graphene is harder than diamonds, and 200 times stronger than the strongest steel. Its ability to conduct heat is 1,000 times greater than copper. It's also the best-known conductor of electricity at room temperature.

It's impermeable to gases—not even helium can pass through it—while being transparent, highly flexible, even stretchable. And get this: if it does get torn, it can r epair itself.

Not surprisingly, this incredible material will transform our lives in the future. It will lead to lighter, faster, more efficient, and much smaller electronics. Lighter, stronger aircraft. New industrial products, like impermeable paint. Consumer products, like better tennis rackets. And because graphene is carbon-based, just as we are, the biotech possibilities are too many to mention.

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Synopsis: Graphite has amazing properties. In 2004, two curious scientists had the patience to peel a single layer just one atom thick from graphite—a 2D carbon material dubbed *graphene*—that amplifies those properties and will transform our future in many ways.

- Graphite is an allotrope of pure carbon, as is diamond, but, ironically, graphite and diamonds have nearly opposite properties, in thermal and electrical conductivity as well as in hardness and appearance.
- Graphite's fantastic conductivity comes from a very special attribute: Its carbon atoms only use three of their four outer energy-level electrons in the graphite's hexagonal lattice-sheet structure; the fourth electron is available to conduct electricity along the sheet but not across sheets.
  - Sheets, which are held together by weaker bonds (called *van der Waals forces*), readily exfoliate when we write with a pencil, which gave scientists an idea: What if you could peel individual one-atom-thick sheets off the graphite? What could you do with it?
  - At the University of Manchester in 2004, scientists peeled and peeled using clear sticky tape until they had a layer just one atom thick—graphene. (Since then, less-painstaking methods of creating graphene have been developed.)
- Graphene is a 2D material with extraordinary properties resulting from the layer of mobile electrons flowing across its entire surface that do not interact with each other but *can* interact with other substances.
- 1 mm of graphite contains 3 million layers of graphene.
- Graphene's amazing properties sound like something out of science fiction! It is:
  - The thinnest compound known to man; at one atom thick, it is thousands of times thinner than a human hair.
  - The lightest material known, about 1,000 times lighter than a sheet of paper.
  - Harder than diamonds.
  - 100–300 times stronger than steel, with a very high tensile stiffness.
  - The best conductor of heat—1,000 times better than copper.
  - The best conductor of electricity at room temperature, with thousands of new electronics patents filed. However, its extreme conductivity in its pure form creates some limitations that researchers are creatively working around.
  - Transparent and has remarkable light-absorption characteristics.
  - Impermeable—not even helium can pass through it—but its surface properties can be modified to be either hydrophobic or hydrophilic.
  - Stretchable and can be made into highly flexible materials.
  - Capable of self-repair by being bombarded with carbon atoms.
  - Able to be layered with other materials at the atomic level to add additional amazing capabilities.

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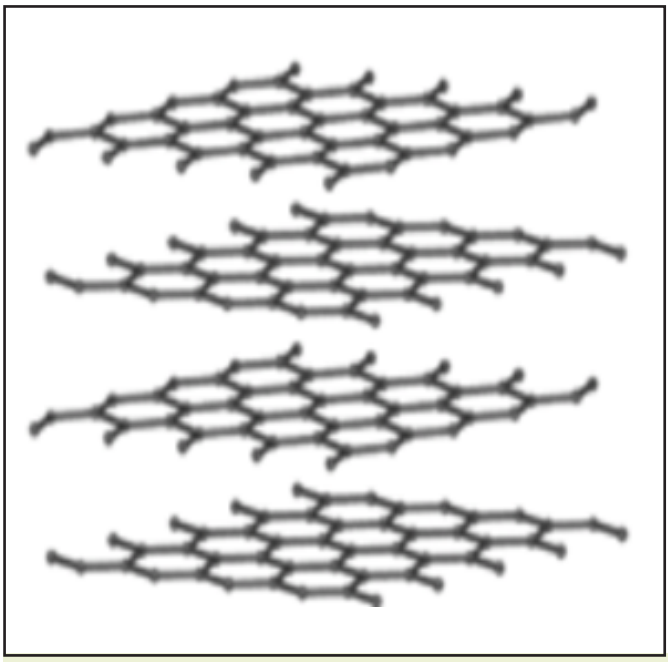
BACKGROUND

- Graphene will transform our lives in the future.
  - It will revolutionize the miniaturization of technology.
  - It could make mobile phones and tablets flexible enough to roll up, incredibly fast and with solar power.
  - Ultrasensitive miniaturized graphene sensors will enable early-warning systems for weather and pollutants, allow detection of chemical weapons and explosives, and boost the effectiveness of monitoring vital crops for the agricultural industry.
  - It has broad biotechnical applications because it is carbon based, like we are.
    - It can be used in drug transport systems, tissue engineering, "smart" implants, and biological agents like antimicrobials.
    - Its sea of electrons even appears to react to cancerous cells, enabling noninvasive sensors for detection of illness.
  - Super-light graphene-oxide membranes form a perfect filtration barrier for both liquids and gasses—useful for water filtration, gas separation, desalination, and CO_2 sequestration.
  - Graphene coatings a single layer thick could protect perishable food and drugs from water and oxygen molecules, keeping them fresher longer.
  - Graphene composites may be the most exciting research area for the future, with limitless possibilities.
    - Aircraft wings made of graphene-based composites would be strong but very light, increasing fuel efficiency and range, as well as decreasing the threat of lightning strikes.
    - Graphene paint could seal ships, cars, and structures to protect them from the oxidation of rust, and even brick and stone on homes could be weatherproofed with graphene-based materials.
    - Graphene-composite tennis rackets are already in production (Head), and enhancement of racing-sports equipment like skis, bikes, and cars is on the horizon.
- Graphene can now be inkjet printed for biocompatible layered electronics.
- Imagine future discoveries made possible by a single layer of carbon atoms peeled from graphite by curious scientists just 13 years ago!



Graphite crystallographic structure with multiple layers. A single layer of carbon is what is known as *graphene*, which is characterized by infinite, two-dimensional sheets of carbon.

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