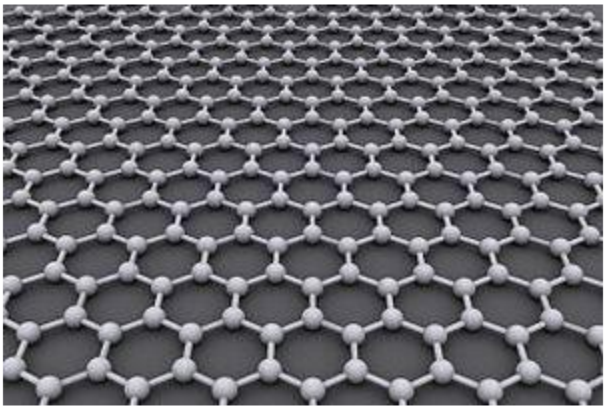
Carbon nanostructures

- Bucky balls
- Carbon nanotubes
- Graphene

What is graphene?

Graphene is made of a single layer of carbon atoms that are bonded together in a repeating pattern of hexagons. Graphene is one million times thinner than paper; so thin that it is actually considered two dimensional.



Carbon is an incredibly versatile element. Depending on how atoms are arranged, it can produce hard diamonds or soft graphite. Graphene's flat honeycomb pattern grants it many unusual characteristics, including the status of strongest material in the world.

These single layers of carbon atoms provide the foundation for other important materials. Graphite — or pencil lead– is formed when you stack graphene. Carbon nanotubes, which are another emerging material, are made of rolled graphene. These are used in bikes, tennis rackets and even living tissue engineering.

Graphene is the two-dimensional crystalline form of carbon whose extraordinary electron mobility and other unique features hold great promise for nanoscale electronics and photonics.. The only problem with graphene is that high-quality graphene is a great conductor that does not have a band gap (it can't be switched off). Therefore to use graphene in the creation of future nano-electronic devices, a band gap will need to be engineered into it, which will, in turn, reduce its electron mobility to that of levels currently seen in strained silicone films. This essentially means that future research and development needs to be carried out in order for graphene to replace silicone in electrical systems in the future.

As with monolayer graphene, bilayer graphene also has a zero bandgap and thus behaves like a metal. But a bandgap can be introduced if an electric displacement field is applied to the two layers; the material then behaves like a semiconductor. A team of researchers from Berkeley has engineered a bandgap in bilayer graphene that can be precisely controlled from 0 to 250 meV. With precision control of its bandgap over a wide range, plus independent manipulation of its electronic states through electrical doping, dual-gated bilayer graphene becomes a remarkably flexible tool for nanoscale electronic devices.

How was it discovered?

Graphene was first studied theoretically in the 1940s. At the time, scientists thought it was physically impossible for a two dimensional material to exist due to thermal instability when separated, so they did not pursue isolating graphene. Decades later, interest picked up and researchers began dreaming up techniques to peel apart graphite. No one had both the tools and interest to reliably isolate free-standing graphene until the early 2000s. It actually become possible due to the fact that the carbon to carbon bonds in graphene are so small and strong that they prevent thermal fluctuations from destabilizing it. They tried wedging molecules between layers of graphene and scraping and rubbing graphite, but they never got to a single layer. Eventually, they were able to isolate graphene on top of other materials, but not on its own.

In 2002, University of Manchester researcher Andre Geim became interested in graphene and challenged a PhD student to polish a hunk of graphite to as few layers as possible. The student was able to reach 1,000 layers, but could not hit Geim’s goal of 10 to 100 layers. Geim tried a different approach: tape. He applied it to graphite and peeled it away to create flakes of layered graphene. More tape peels created thinner and thinner layers, until he had a piece of graphene 10 layers thick. Geim’s team worked at refining their technique and eventually produced a single layer of carbon atoms. They published their findings in “Science” in October 2004. Geim and his colleague Kostya Novoselov received the Nobel Prize in physics in 2010 for their work.

Since those first flakes made with tape, graphene production has improved at a rapid pace. In 2009, researchers were able to create a film of graphene that measured 30 inches across.

Graphene production

The quality of graphene plays a crucial role as the presence of defects, impurities, grain boundaries, multiple domains, structural disorders, wrinkles in the graphene sheet can have an adverse effect on its electronic and optical properties.

In electronic applications, the major bottleneck is the requirement of large size samples, which is possible only in the case of chemical vapor deposition (CVD) process, but it is difficult to produce high quality and single crystalline graphene thin films possessing very high electrical and thermal conductivities along with excellent optical transparency.

Another issue of concern in the synthesis of graphene by conventional methods involves the use of toxic chemicals and these methods usually result in the generation hazardous waste and poisonous gases. Therefore, there is a need to develop green methods to produce graphene by following environmentally friendly approaches.

Why is it unusual?

Geim and Novoselov's paper was wildly interesting to other scientists because of its description of graphene's strange physical properties. Electrons move through graphene incredibly fast and begin to exhibit behaviors as if they were massless, mimicking the physics that governs particles at super small scales.

"That kind of interaction inside a solid, so far as anyone knows, is unique to graphene," wrote Geim and another famous graphene researcher, Philip Kim, in a 2008 Scientific American article. "Thanks to this novel material from a pencil, relativistic quantum mechanics is no longer confined to cosmology or high-energy physics; it has now entered the laboratory."

Some of important Graphene's special properties are:

Conductive: Tests have shown that the electronic mobility of graphene is very high, with previously reported results above 15,000 $cm^2 \cdot V^{-1} \cdot s^{-1}$ and theoretically potential limits of 200,000 $cm^2 \cdot V^{-1} \cdot s^{-1}$ (limited by the scattering of graphene's acoustic photons). It is said that graphene electrons act very much like photons in their mobility due to their lack of mass. These charge carriers are able to travel sub-micrometer distances without scattering; a phenomenon known as ballistic transport. However, the quality of the graphene and the substrate that is used will be the limiting factors. With silicon dioxide as the substrate, for example, mobility is potentially limited to 40,000 $cm^2 \cdot V^{-1} \cdot s^{-1}$.Electrons are the particles that make up electricity. So when graphene allows electrons to move quickly, it is allowing electricity to move quickly. It is known to move electrons 200 times faster than silicon because they travel with such little interruption. Electrical resistivity for Graphene is 10 nΩ·m (at 20 °C) and that of Cu is 16.78 nΩ·m (at 20 °C).

It is also an excellent heat conductor and works normally at room temperature. The measured thermal conductivity of graphene is in the range 3000 – 5000 W/mK at room temperature much higher than metals, for example for Cu i.e. 401 W/mK.

Strong: Another of graphene's stand-out properties is its inherent strength. Due to the strength of its 0.142 nm-long carbon bonds, graphene is the strongest material ever discovered, with an ultimate tensile strength of 130,000,000,000 Pascals (or 130 gigapascals), compared to 400,000,000 for A36 structural steel, or 375,700,000 for Aramid (Kevlar). Not only is graphene extraordinarily strong, it is also very light as 0.77milligrams per square metre (for comparison purposes, 1 square metre of paper is roughly 1000 times heavier). It is often said that a single sheet of graphene (being only 1 atom thick), sufficient in size enough to cover a whole football field, would weigh under 1 single gram.

Flexible: What makes this particularly special is that graphene also contains elastic properties, being able to retain its initial size after strain. Those strong bonds between graphene's carbon atoms are also very flexible. They can be twisted, pulled and curved to a certain extent without breaking, which means graphene is bendable and stretchable. In 2007, Atomic force microscopic (AFM) tests were carried out on graphene sheets that were suspended over silicone dioxide cavities. These tests showed that graphene sheets (with thicknesses of between 2 and 8 nm) had spring constants in the region of 1-5 N/m and a Young's modulus (different to that of three-dimensional graphite) of 0.5 TPa. Again, these superlative figures are based on theoretical prospects using graphene that is unflawed containing no imperfections whatsoever and currently very expensive and difficult to artificially reproduce, though production techniques are steadily improving, ultimately reducing costs and complexity.

Transparent (Optical properties): Graphene's ability to absorb a rather large 2.3% of white light is also a unique and interesting property, especially considering that it is only 1 atom thick. Adding another layer of graphene increases the amount of white light absorbed by approximately the same value (2.3%).Graphene absorbs 2.3 percent of the visible light that hits it, which means you can see through it without having to deal with any glare.

What can it be used for?

The use of graphene in everyday life is not far off, due in part to existing research into carbon nanotubes — the rolled, cylindrical version of graphene. The tubes were popularized by a 1991 paper and touted for their incredible physical qualities, most of which are very similar to graphene. But it is easier to produce large sheets of graphene and it can be made in a similar way to silicon. Many of the current and planned applications for carbon nanotubes are now being adapted to graphene.

Some of the biggest emerging applications are:

Solar cells: Solar cells rely on semiconductors to absorb sunlight. Semiconductors are made of an element like silicon and have two layers of electrons. At one layer, the electrons are calm and stay by the semiconductor's side. At the other layer, the electrons can move about freely, forming a flow of electricity. Solar cells work by transferring the energy from light particles to the calm electrons, which become excited and jump to the free-flowing layer, creating more electricity. Graphene's layers of electrons actually overlap, meaning less light energy is needed to get the electrons to jump between layers. In the future, that property could give rise to very efficient solar cells. Using graphene would also allow cells that are hundreds of thousands of times thinner and lighter than those that rely on silicon.

Transistors: Computer chips rely on billions of transistors to control the flow of electricity in their circuits. Research has mostly focused on making chips more powerful by packing in more transistors, and graphene could certainly give rise to the thinnest transistors yet. But transistors can also be made more powerful by speeding the flow of electrons — the particles that make up electricity. As science approaches the limit for how small transistors can be, graphene could push the limit back by both moving electrons faster and reducing their size to a few atoms or less.

Transparent screens: Devices such as plasma TVs and phones are commonly coated with a material called indium tin oxide. Manufacturers are actively seeking alternatives that could cut costs and provide better conductivity, flexibility and transparency. Graphene is an emerging option. It is non-reflective and appears very transparent. Its conductivity also qualifies it as a coating to create touch screen devices. Because graphene is both strong and thin, it can bend without breaking, making it a good match for the bendable electronics that will soon hit the market.
Graphene could also have applications for camera, sensors, DNA sequencing,gas sensing, material strengthening, water desalination and beyond.

Energy Storage

One area of research that is being very highly studied is energy storage. While all areas of electronics have been advancing over a very fast rate over the last few decades (in reference to Moore's law which states that the number of transistors used in electronic circuitry will double every 2 years), the problem has always been storing the energy in batteries and capacitors when it is not being used. These energy storage solutions have been developing at a much slower rate. The problem is this: a battery can potentially hold a lot of energy, but it can take a long time to charge, a capacitor, on the other hand, can be charged very quickly, but can't hold that much energy (comparatively speaking). The solution is to develop energy storage components such as either a supercapacitor or a battery that is able to provide both of these positive characteristics without compromise.

Currently, scientists are working on enhancing the capabilities of lithium ion batteries (by incorporating graphene as an anode) to offer much higher storage capacities with much better longevity and charge rate. Also, graphene is being studied and developed to be used in the manufacture of supercapacitors which are able to be charged very quickly, yet also be able to store a large amount of electricity. Graphene based micro-supercapacitors will likely be developed for use in low energy applications such as smart phones and portable computing devices and could potentially be commercially available within the next 5-10 years.

Graphene-enhanced lithium ion batteries could be used in much higher energy usage applications such as electrically powered vehicles, or they can be used as lithium ion batteries are now, in smartphones, laptops and tablet PCs but at significantly lower levels of size and weight.

Composite Materials

Graphene is strong, stiff and very light. Currently, aerospace engineers are incorporating carbon fibre into the production of aircraft as it is also very strong and light. However, graphene is much stronger whilst being also much lighter. Ultimately it is expected that graphene is utilized (probably integrated into plastics such as epoxy) to create a material that can replace steel in the structure of aircraft, improving fuel efficiency, range and reducing weight. Due to its electrical conductivity, it could even be used to coat aircraft surface material to prevent electrical damage resulting from lightning strikes. In this example, the same graphene coating could also be used to measure strain rate, notifying the pilot of any changes in the stress levels that the aircraft wings are under. These characteristics can also help in the development of high strength requirement applications such as body armour for military personnel and vehicles

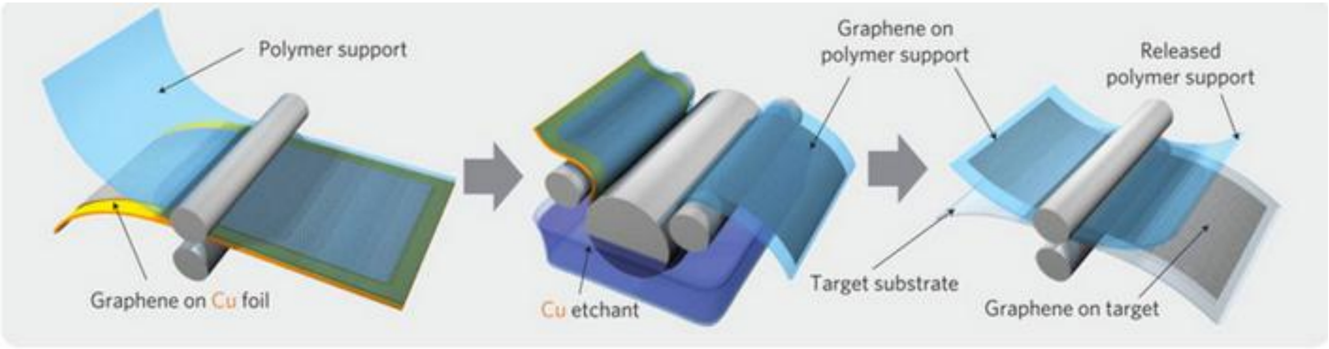
Ultrafiltration

Another standout property of graphene is that while it allows water to pass through it, it is almost completely impervious to liquids and gases (even relatively small helium molecules). This means that graphene could be used as an ultrafiltration medium to act as a barrier between two substances. The benefit of using graphene is that it is only 1 single atom thick and can also be developed as a barrier that electronically measures strain and pressures between the 2 substances (amongst many other variables).

A team of researchers at Columbia University have managed to create monolayer graphene filters with pore sizes as small as 5nm (currently, advanced nanoporous membranes have pore sizes of 30-40nm). While these pore sizes are extremely small, as graphene is so thin, pressure during ultrafiltration is reduced. Co-currently, graphene is much stronger and less brittle than aluminium oxide (currently used in sub-100nm filtration applications). What does this mean? Well, it could mean that graphene is developed to be used in water filtration systems, desalination systems and efficient and economically more viable biofuel creation.

What are the critiques?

Graphene is still in an infantile stage compared to developed materials like silicon and Indium tin oxide (ITO). In order for it to be widely adopted, it will need to be produceable in large quantities at costs equal to or lower than existing materials. Emerging roll-to-roll, vapor deposit and other production techniques hint that this is possible, but they’re not yet ready to bring graphene to every mobile device screen out there. Researchers will also need to continue to work at improving graphene’s transparency and conductivity in its commercial form.



Roll-to-roll manufacturing could allow graphene to be made at large scales. Korea University

While graphene shows promise for transistors, it has a major problem: It can't switch the flow of electricity "off" like materials such as silicon, which means the electricity will flow constantly. That means graphene can't serve as a transistor on its own. Researchers are now exploring ways to adjust it and combine it with other materials to overcome this limitation. One technique involves placing a layer of boron nitride–another one-atom-thick material–between two layers of graphene. The resulting transistor can be switched on and off, but the electrons' speed is slowed somewhat. Another technique involves introducing impurities into graphene.

Graphene may also be emerging too late for many of its possible applications. Electric car batteries and carbon fiber could be made with graphene, but they already rely on activated carbon and graphite, respectively — two very inexpensive materials. Graphene will remain more expensive for the time being, and may never be inexpensive enough to convince manufacturers to switch.

The world is only a decade into exploring what it can do with graphene. In contrast, silicon has been around for nearly 200 years. At the pace research is moving, we could know very soon if graphene will become ubiquitous or just another step in discovering the next wonder material.

Carbon Nanotubes

What is a Carbon Nanotube?

A Carbon Nanotube is a tube-shaped material, made of carbon, having a diameter measuring on the nanometer scale. The graphite layer appears somewhat like a rolled-up chicken wire with a continuous unbroken hexagonal mesh and carbon molecules at the apexes of the hexagons.

Carbon Nanotubes have many structures, differing in length, thickness, and in the type of helicity and number of layers. Although they are formed from essentially the same graphite sheet, their electrical characteristics differ depending on these variations, acting either as metals or as semiconductors.

As a group, Carbon Nanotubes typically have diameters ranging from <1 nm up to 50 nm. Their lengths are typically several microns, but recent advancements have made the nanotubes much longer, and measured in centimeters.

Carbon Nanotubes can be categorized by their structures as:

- Single-wall Nanotubes (SWNT)
- Multi-wall Nanotubes (MWNT)
- Double-wall Nanotubes (DWNT)

What are the Potential Applications for Carbon Nanotubes?

Carbon Nanotube Technology can be used for a wide range of new and existing applications:

- Conductive plastics
- Structural composite materials
- Flat-panel displays
- Gas storage
- Antifouling paint
- Micro- and nano-electronics
- Radar-absorbing coating
- Technical textiles
- Ultra-capacitors
- Atomic Force Microscope (AFM) tips
- Batteries with improved lifetime
- Biosensors for harmful gases
- Extra strong fibers

Electronic transport in carbon-nanotubes

A metallic carbon nanotube can be considered as a very thin wire, but the conduction of charge is very different from a normal macroscopic piece of wire. However, individual carbon nanotubes would be able to carry useful amounts of current (~µA each) around a nanoscale device. Their use in electronics, however, could well emerge before truly nanoscale devices are available.

In conventional Si-based integrated circuits the demand for ever smaller components and thinner Cu wires between the components (interconnects) is producing a serious heating problem. The thickness of the Cu interconnects is approaching 100 nm; and it is not just that the thinner wires have a higher resistance, but it becomes more difficult to maintain uniformity in the wire without faults and hot spots. Major chip manufacturers such as Intel are actively researching the use of carbon nanotubes as interconnects.

Table 2. Transport Properties of Conductive Materials

Material	Thermal Conductivity (W/m.k)	Electrical Conductivity
Carbon Nanotubes	> 3000	10^6 - 10^7
Copper	400	6 x 107
Carbon Fiber - Pitch	1000	2 - 8.5 x 10^6
Carbon Fiber - PAN	8 - 105	6.5 - 14 x 10^6

In the automotive industry, carbon nanotubes impart conductivity to plastic exterior parts, such as fenders, mirror housings, and door handles, which are subjected to the **electrostatic painting** process.

Carbon Nanotubes have been incorporated, too, in thermoplastics as substitutes for old metallic-made automotive parts, thus **decreasing the weight** of the parts by more than 50% in some cases.

This combination of Carbon Nanotubes unique properties and various product forms with the newer and compatible modern processing technologies, now offers unseen possibilities for creating new engineered materials for automotive applications.

Mechanical properties

The carbon nanotubes are the strongest materials known. The strength arises from the strong covalent *sp*2 bonds among the carbon atoms in a graphene sheet, and it is not much different in nanotubes.

Table 1. Mechanical Properties of Engineering Fibers

Fiber Material	Specific Density	E (TPa)	Strenght (GPa)	Strain at Break (%)
Carbon Nanotube	1.3 - 2	1	10 - 60	10

HS Steel	7.8	0.2	4.1	< 10
Carbon Fiber - PAN	1.7 - 2	0.2 - 0.6	1.7 - 5	0.3 - 2.4
Carbon Fiber - Pitch	2 - 2.2	0.4 - 0.96	2.2 - 3.3	0.27 - 0.6
E/S - glass	2.5	0.07 / 0.08	2.4 / 4.5	4.8
Kevlar* 49	1.4	0.13	3.6 - 4.1	2.8

Kevlar is a registered trademark of DuPont.

In the Marine industry, Carbon Nanotubes have been integrated into **composites** for mechanical reinforcement.

For sailing vessels, they can improve their mechanical resistance and durability while significantly reducing their total weight. For all of the other parts where lighter weight needs to be combined with higher mechanical resistance,.

The carbon nanotubes marine coating prevents waterborne organisms from adhering strongly to the coating.

The use of composite materials in the sporting goods industry has grown exponentially. These products offer sporting goods designers and manufacturers, an integrated and innovative technology for improving the strength, fracture toughness, shelf life, and antistatic properties in composite parts. Common applications include bike frames, hockey sticks, tennis rackets, golf shafts, and skis and so has the demand for carbon nanotubes products.

Carbon nanotubes based products also offers architects, specifiers, engineers and builders an array of flexible and cost-efficient solutions

Thermal properties

Having observed all the other remarkable properties of nanotubes, it should be no surprise that they also display a huge thermal conductivity. The Aeronautic sector is using carbon nanotubes for flame retardant protection of fuel tanks and exhaust parts.

Optical properties

Photograph of the size dependent emission spectra of both HgS and CdSe quantum dots show that Small quantum dots absorb and emit blue/green light, larger dots absorb and emit red light.