Carbon Nanotubes Activity Guide

Quick Reference Activity Guide

Activity Materials

chicken wire models of different nanotube types
description pages for counting schemes
solid models for graphite and diamond structures

Starting Points

Have you learned about the elements in school? Elements are types of atoms. They make up all of the things around us. Carbon is one of the most abundant elements on Earth. We're going to talk about the different structures of carbon.

Can you name some forms of carbon? Hints: Some people wear rings made from it, and most of you probably use another form to write everyday in class. Diamond is one form of carbon; the graphite used in pencils is another.

Hold up the solid models of diamond and graphite, and explain that each plastic sphere represents an atom. Ask the students to make some observations about these two structures. Then, focus their responses with the following question: How are the two structures different? Diamond has connections (bonds) occurring in all three dimensions, which makes the structure very rigid. That's why diamond is the hardest natural material known and why diamond can cut glass. On the other hand, graphite has connections in two dimensions that form sheets of carbon, called graphene sheets. These graphene sheets stack one on top of another and easily slip off the pencil onto the paper when we write. Even though these materials are made of the exact same element – carbon, the atoms can arrange in such a way to make one of the hardest materials *and* one of the softest.

Now, imagine taking one graphene sheet and rolling it up into a cylinder – this is a new form of carbon called a nanotube, another form looks like a nano-sized soccerball.

Demonstration Procedures

Use starting points to introduce the four forms of carbon to be discussed - diamond, graphite, fullerenes, carbon nanotubes.

Compare the sheet of chicken wire to the solid model of graphite. The sheets have the same hexagonal pattern. Explain that we will pretend that there is a carbon atom at each intersection on the sheet.

Use the sheet to demonstrate how a carbon nanotube can be formed by bending the sheet so that the opposite edges touch. Note that if you roll it up in different ways then you get different patterns. Show the three pre-rolled nanotube models.

Explain that scientists have found that these different types of carbon nanotubes have slightly different structures which change their properties. Because of this scientists have developed a scheme to classify nanotubes - armchair, zigzag, chiral. Show the three models and ask the students to look for the different patterns they make.

Describe the classification scheme involving counting along a path around the tube, starting and ending at the same point. Hold the starting point between the finger and thumb of one hand and use the other hand to count around the tube. The zig-zag model is the easiest one to count and the best one to start with. Count each carbon atom around the tube - (1,0) (2,0) (3,0) (4,0) (5,0) etc. – until you get back to the starting point.

Next show the counting on an armchair model. As you count around the tube, note that you are counting at an angle and it will not be possible to get back to your starting point unless you turn a corner. Note that you have to pick the right place to turn so that you end up at your starting point because you can only turn once. Again, count each carbon atom around the tube - (1,0) (2,0) (3,0) (4,0) (5,0) – until you get to a corner; after you turn the count continues as - (5,1) (5,2) (5,3) (5,4) etc. - until you get back to the starting point. The chiral model can be counted similarly.

Fact Sheet

Carbon has atomic number of 6 and an atomic weight of 12.

How are carbon nanotubes made?
Classic method. Electric arc discharge. A current is passed between two graphite rods, one acting as an anode and one as a cathode, forming a hot, bright arc of electricity that vaporizes carbon from the anode and generates a plasma of carbon. The carbon recondenses on the cathode to form **multi-walled carbon nanotubes**.

Single-walled carbon nanotube synthesis. laser ablation, metal catalysts

Synthetic challenges. One of the current challenges in CNT research is developing a synthetic technique for growing SWNTs of an exact type, in an exact quantity, and with an exact orientation.

The structures of the nanotubes can be correlated with their physical properties such as

- **Mechanical properties (tensile strength)** Based on small-scale experiments and theoretical calculations, a one-inch thick rope of CNTs is predicted to be 100 times stronger than steel and 1/6 the weight of steel.
- **Thermal conductivity properties** CNTs are good thermal conductors.
- **Electrical conductivity properties** Nanotubes have semiconducting properties (some zig-zag, chiral); metallic properties (armchair, some zigzag).

Carbon nanotubes are currently being used (•) or considered (∇) for a number of significant applications (see Background for more details):

- **AFM probe tips.**
- **Flat panel display screens.**
- **Microelectromechanical devices.**

∇ **Hydrogen storage.**
∇ **Actuators/Artificial muscles.**
∇ **Chemical sensors.**
∇ **Nanoscale electronics/nanocomputing.**
∇ **Nanothermometer**.
∇ **Flash photography and carbon nanotubes**.

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Background an Supporting Information

Background

By middle school, kids have learned about the elements and they have been introduced to the concept of the atom. When starting this activity it will be important to remind them of what they know – atoms are the building block of everything around them, elements are different kinds of atoms – and build on this knowledge to teach them something new. The carbon nanotube activity is a great way to build on their understanding of atoms and the elements, and teach them something new about nanotechnology. To do this you might also need to help them understand how small nano is and why it is exciting for scientists and engineers to create materials and devices at the nanoscale. (Refer to the "How Small is Nano?" Activity Guide.)

Carbon is the most abundant element on our planet. Many students will know that it makes up a major percentage of the element in our body and is included in the air as well as many other materials around us. This is important to acknowledge, but we are just focussing on structures made up of only carbon and no other elements.

Most students will be familiar with diamond and graphite and may even know that these materials are made up of carbon. Diamond is the hardest substance found in nature (a diamond ring can scratch glass easily), but graphite is one of the softest (pencils use graphite to make a black mark, and graphite is also often used as a lubricant to allow two surfaces to slide freely). With a little help and encouragement, students will be able to identify graphite and diamonds (pencils and engagement rings). Give them the opportunity to brainstorm the different properties associated with each material. Both are made up only of carbon atoms, but these atoms are arranged very differently (diamond = tetragonal; graphite = hexagonal sheet, each atom bonded to three others). The differences between these two types of carbon arise at the nanoscale – when the structure of carbon atoms have different arrangements. Nature gave us these two types of carbon, but scientists have been able to create other forms of carbon - fullerenes and nanotubes. Our goal in this activity is introduce the structures and properties of the four types of carbon. Be sure to allow the students to see and play with the structures of each form of carbon.

As demonstrated by the dramatic difference between diamond and graphite, we expect these other forms of carbon to also have very different properties. Scientists can look at these other forms of carbon – using special microscopes that can see at the nanoscale - to learn more about how the atoms in these different forms of carbon are arranged. This is how fullerenes and carbon nanotubes were discovered. Originally these forms of carbon were made in a rather crude way, by zapping graphite with a high energy laser until most of the graphite was gone and in the material that is left over we found a few nanotubes. After carbon nanotubes were discovered, other scientists and engineers devised more efficient ways to make carbon nanotubes and now they can grow carbon nanotubes from a surface. Interestingly, some speculate that carbon nanotubes and other fullerenes were grown long before the actual discovery and it wasn't until instrumentation was developed for nanotechnology research that these materials became detectable. So, nanotechnology was essential for discovering carbon nanotubes and can be used to grow the carbon nanotubes.

The students should be introduced to fullerenes, which are soccer ball-shaped molecules that consist of 60 carbon atoms. This unusual shape can be found in many different places such as sports (soccer balls and new golf balls), architecture, and art (examples of each will be shown). These molecules were named after an architect, Buckminster Fuller, who was responsible for the design of the first geodomes. A geodome that many kids will be able to recognize is "Spaceship Earth" at Epcot Center (Disney World). Fullerenes consist of hexagons and pentagons that form a spherical shape. Fullerenes have also been proposed as possible HIV inhibitors as well as potential constituents in interstellar space. In 1996, the Nobel Prize in Chemistry was awarded for the discovery of fullerenes. These molecules are relatively new to the field of chemistry as they were first discovered in 1985, but their structure has been seen through history.

Carbon nanotubes, the most recent discovery of a form of carbon, should also be introduced. These molecules are shaped like a tube (imagine a sheet of graphite, or "graphene sheet", rolled into a tube). Carbon nanotubes also come in different flavors. These flavors can be classified by how the carbon sheet is wrapped into a tube. The students will be introduced to the three types of nanotubes, armchair, zig-zag, and chiral [e.g. zig-zag (n, 0); armchair (n, n); and chiral (n, m)]. These materials are relatively new and potential applications are in the making. Like many things in nature, subtle differences in the structure of something changes the behavior that it exhibits.

How are carbon nanotubes made?

The "classic method" of growing CNTs is using an electric arc discharge. Two graphite rods, one acting as an anode and one as a cathode, are placed close together in an inert environment of He gas. A current is passed between the two rods forming a hot, bright arc of electricity that vaporizes carbon from the anode and generates a plasma of carbon and helium. The carbon from the plasma recondenses on the cathode to form multi-walled carbon nanotubes. The presence of an electric field in the arc discharge method seems to promote the growth of longer tubes.

In 1996, Richard Smalley reported a way to synthesize single-walled carbon nanotubes. Instead of an electric arc, a laser is used to form a carbon vapor from a heated (1200C) graphite rod. An inert carrier gas (Helium or Argon) carries the carbon vapor from the 1200C graphite rod to a water-cooled "cold-finger" where the carbon vapor recondenses to form SWNTs.

A metallic catalyst (Fe, Co, Ni) – in the form of either a nanoparticles or a thin film – can be used to enhance the production of carbon nanotubes. Usually a hydrocarbon gas is adsorbed onto the surface of one side of the metal particle and diffuses through the metal coming out on the opposite side to form the carbon nanotube.

One of the current challenges in CNT research is developing a synthetic technique for growing SWNTs of an exact type, in an exact quantity, and with an exact orientation. Scientists would also like to grow very long ropes and bundles of SWNTs. The longest grown CNTs to date are 8 inches long reported in Science by RPI.

Carbon nanotubes are currently being used (•) or considered (∇) for a number of significant applications:

∇ **AFM probe tips.** Single-walled carbon nanotubes have been attached to the tip of an AFM probe to make the tip "sharper". This allows much higher atomic resolution of the surface under investigation. Also, the flexibility of the nanotube prevents damage to the sample surface and the probe tip if the probe tip happens to "crash" into the surface. Piezomax a company started by Max Legally, director of MRSEC's IRG 1, that attaches carbon nanotubes to AFM probes for the purpose of increased resolution as well as decreased wear on sample and probe tip. (see http://www.piezomax.com/index2.html)

∇ **Flat panel display screens.** When a nanotube is put into an electric field, it will emit electrons from the end of the nanotube like a small cannon. If those electrons are allowed to bombard a phosphor screen then an image can be created. Several companies (SI Diamond, Samsung) are using this technology to replace the bulky electron guns of conventional television sets with these significantly smaller carbon nanotube electron guns. When scientists instead use millions of carbon nanotubes as tiny electron guns, the required dimensions change and the creation of a flat panel display (that can hang on your wall) becomes possible. In fact, some advertising billboards have already be made and are being used. (see http://www.sidiamond.com/) Learn more about how conventional televisions work at www.howstuffworks.com. Learn more about a flat panel display prototype: Wang, Q.H., Yan, M., and Chang. *Appl. Phys. Lett.* **78**, 1294 (2001).

• **Microelectromechanical devices.** Dr. Morinobu Endo at Shinshu University mixed nylon with carbon *fibers* (not nanotubes) 100-200 nm in diameter creating a nanocomposite materials that could be injected into the world's smallest (as of 2/6/2002) gear mold. The carbon fibers have good thermal conductivity properties that cause the nanocomposite material to cool more slowly and evenly allowing for better molding characteristics of the nanocomposite. The "improved" properties of the nanocomposite allow it more time to fill the tiny micron-sized mold than nylon would by itself. The tiny gears currently are being made in collaboration with Seiko for use in watches. (see http://www.rpi.edu/web/News/NYTNanotubes.htm)

∇ **Hydrogen storage.** When oxygen and hydrogen react in a fuel cell, electricity is produced and water is formed as a byproduct. If industry wants to make a hydrogen-oxygen fuel cell, scientists and engineers must find a safe way to store hydrogen gas needed for the fuel cell. Carbon nanotubes may be a viable option. Carbon nanotubes are able to store hydrogen and could provide the safe, efficient, and cost-effective means to achieve this goal. Dillon, A.C. et al. *Science*. **286**, 1127 (1999)

∇ **Actuators/Artificial muscles.** An actuator is a device that can induce motion. In the case of a carbon nanotube actuator, electrical energy is converted to mechanical energy causing the nanotubes to move. Two small pieces of "buckypaper," paper made from carbon nanotubes, are put on either side of a piece of double-sided tape and attached to either a positive or a negative electrode. When current is applied and electrons are pumped into one piece of buckypaper and the nanotubes on that side expand causing the tape to curl in one direction. This has been called an artificial muscle, and it can produce 50 to 100 times the force of a human muscle the same size. Applications include: robotics, prosthetics. Learn more about carbon nanotube actuators: Baughman, R.H. et al. *Science.* **284**, 1340 (1999).

- **Chemical sensors.** Semiconducting carbon nanotubes display a large change in conductance in the presence of certain gases (e.g., NO_2 and NH_3). When compared to conventional sensors, carbon nanotubes provide the advantages of a smaller size, an increased sensitivity, and a faster response. Wei, Q.-H. et al. *Science.* **287**, 622 (2000).
- **Nanoscale electronics/nanocomputing** Scientists have exploited the mechanical and electrical properties of carbon nanotubes to produce molecular electronic devices. When nanotubes are placed in a grid, the intersections of the nanotubes become bits of information that can be stored non-volatilely. (see more information at Prof. Charles Lieber's website http://cmliris.harvard.edu/html_natalya/research/research.htm) Semiconducting nanotubes also can be used as single molecule transistors.
- **Nanothermometer**. A carbon nanotube can be partially filled with gallium metal. When the temperature is changed, the gallium metal expands or contracts to fill or empty the carbon nanotube. The gallium level in the carbon nanotube varies almost linearly with temperature. This new device may find use in certain microscopies.
- **Flash photography and carbon nanotubes**. Scientists have discovered that as-grown single-walled carbon nanotubes can be ignited by holding a conventional camera flash a few centimeters away and flashing the sample.

Additional Demonstrations and Experiments

Several accompanying demonstrations can be used to supplement the basic carbon nanotube demonstration discussed above.

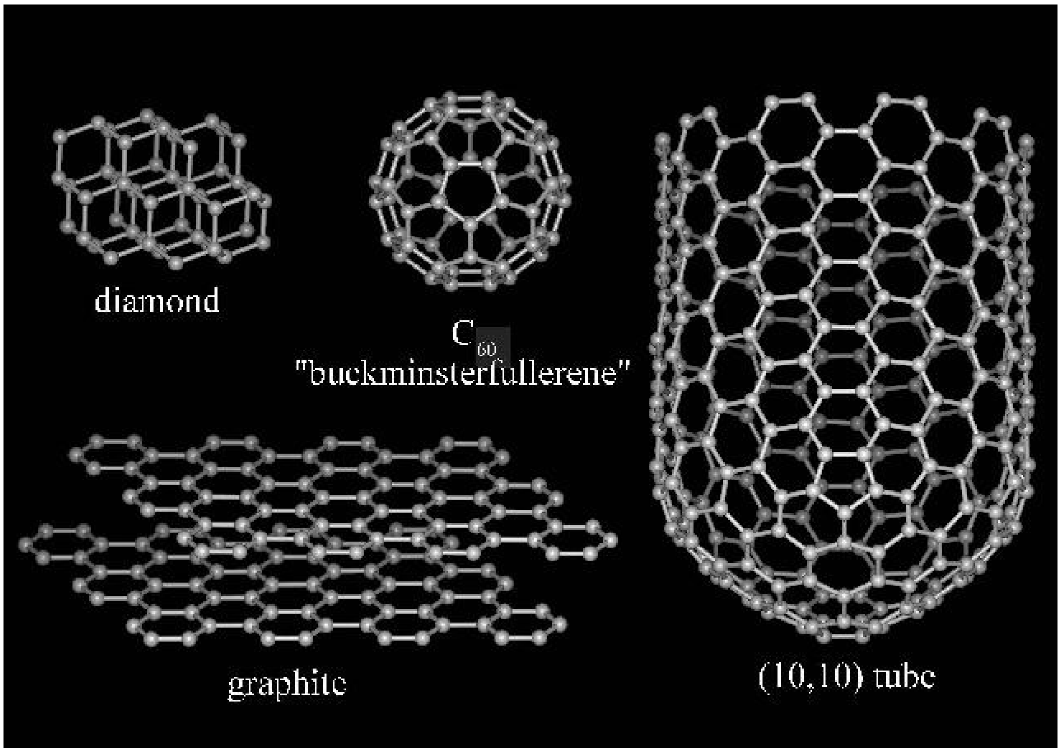
In some outreach venues a giant five foot tall carbon nanotube model is used. After learning how to classify and count carbon nanotubes, students can be asked to try out their new skills on the giant model. If they are successful in classifying the giant model (or close) the students can spin the prize wheel and take away a give-away item.

When discussing the different properties of the different forms of carbon, the thermal conductivity of diamond (diamond tip scribes held against ice) and electrical conductivity of graphite can be demonstrated.

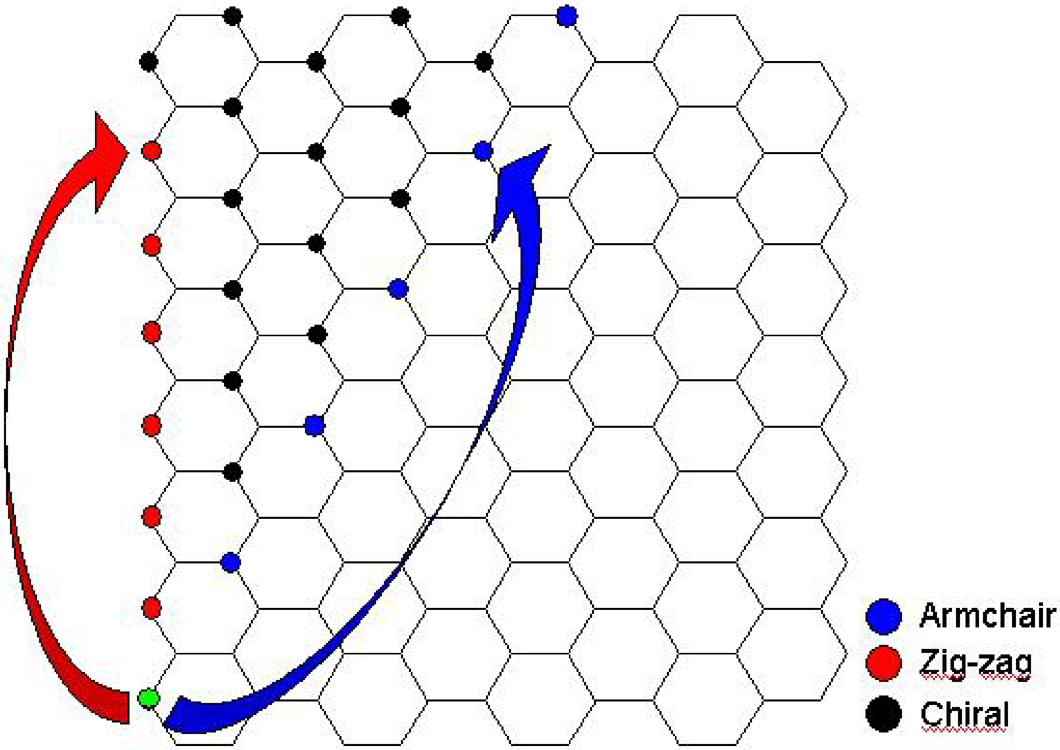
When discussing the form of fullerenes, the students can be given the opportunity to put together a paper model of a fullerene (either C_{60} or C_{70}).

When discussing the superconducting properties of fullerenes, the effect can be demonstrated with the demonstration that places a magnet "magically floating" above a superconducting plate.

In addition to the chicken wire models, pencils with the three basic types of nanotubes printed on them may also be available. Each student can be given a pencil (Each pencil will have the design of one of the types of nanotubes) and will have to figure out which type of nanotube they are holding.



Four forms of carbon slide created by Prof. Richard Smalley of Rice University.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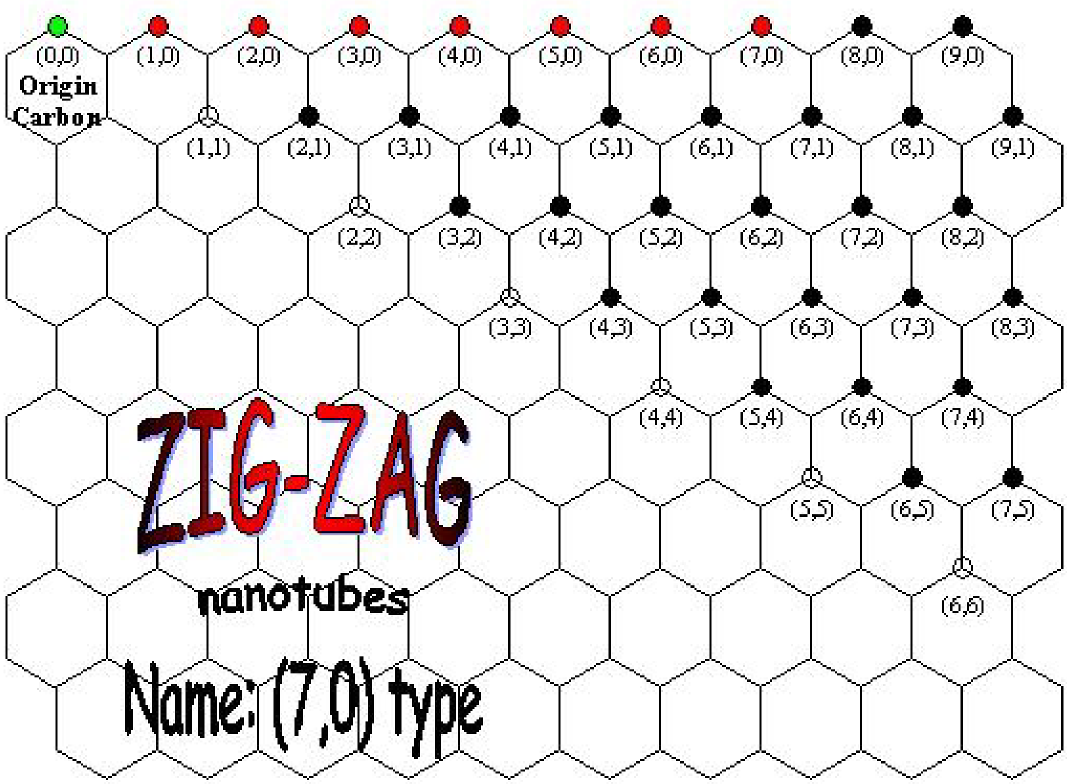
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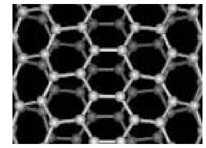

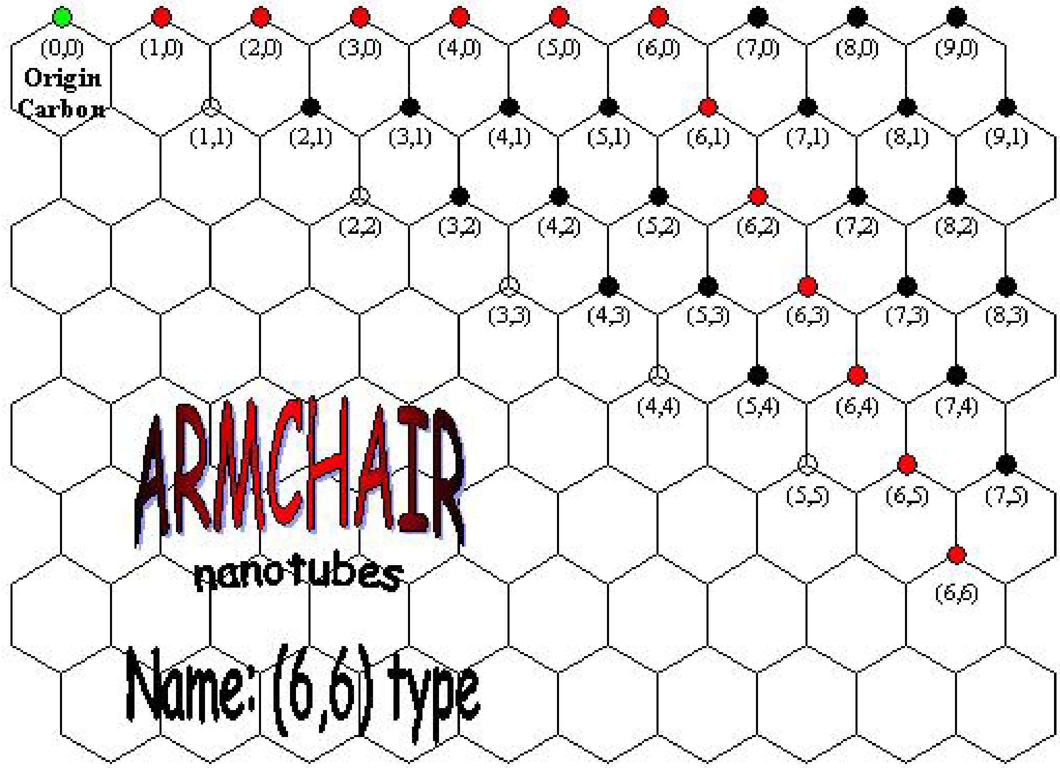
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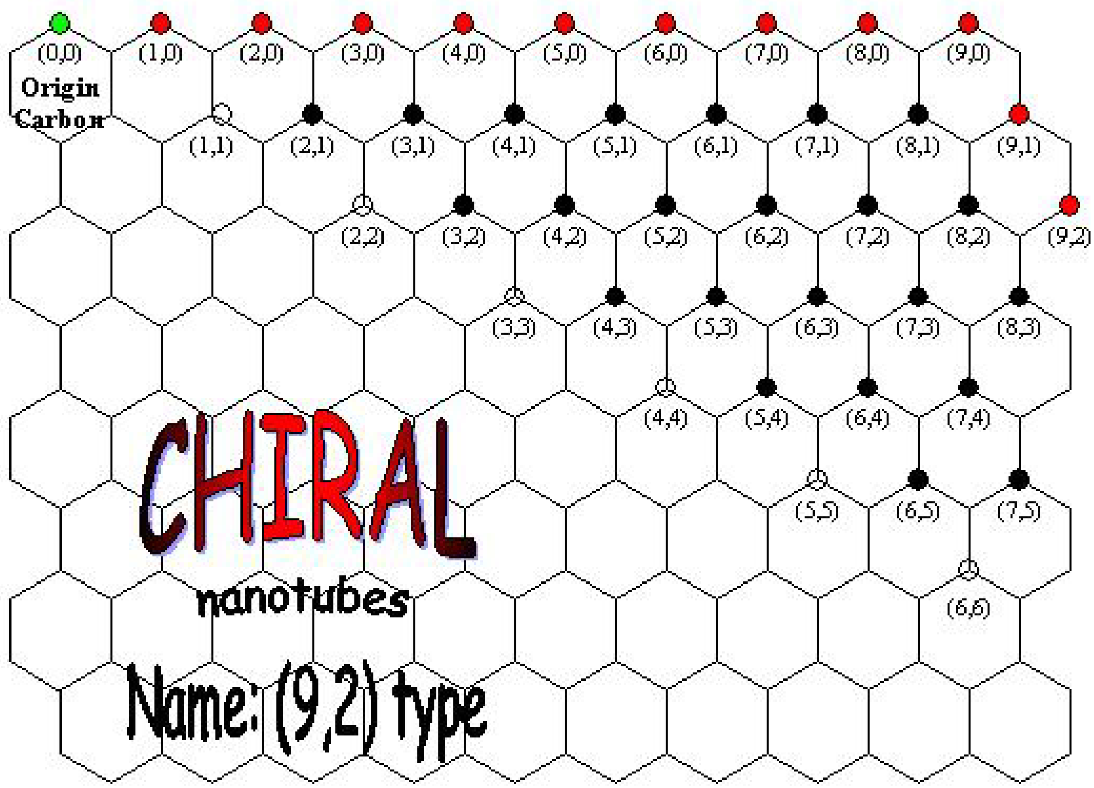
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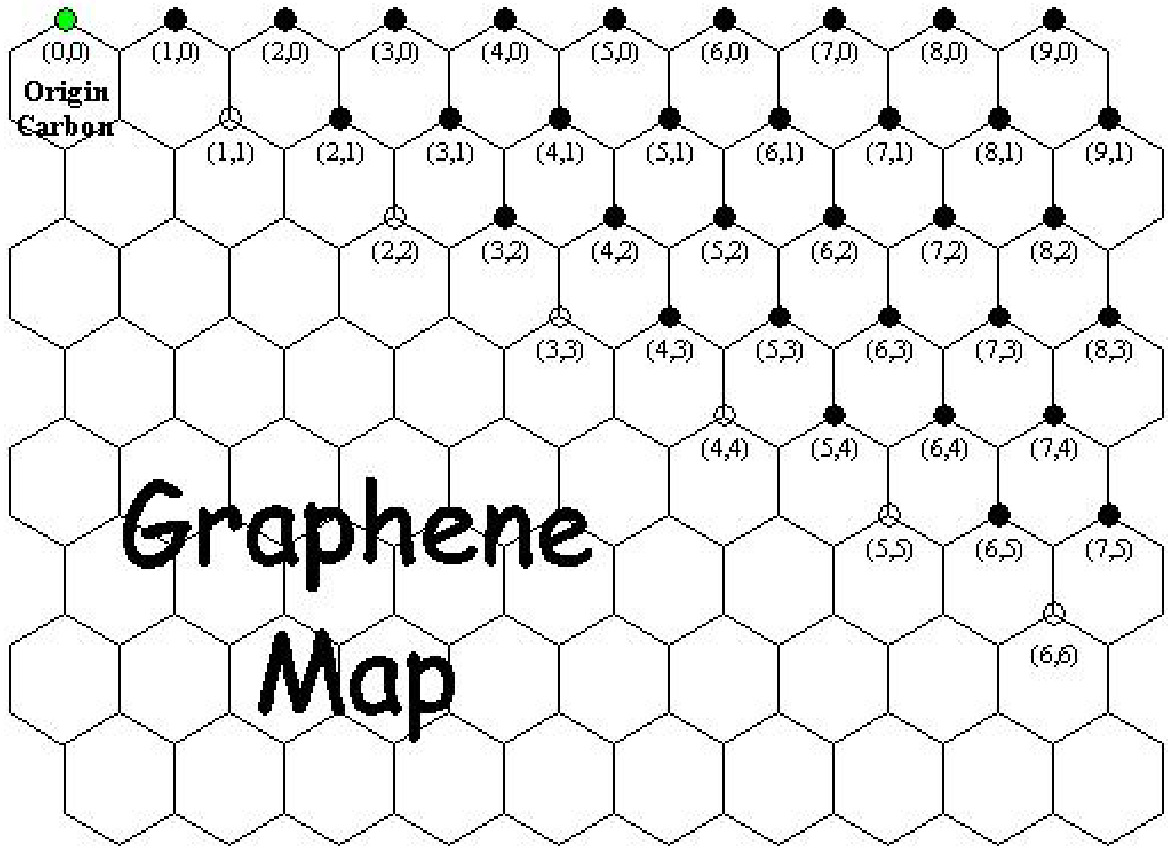
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