CARBON ALLOTROPES

The Same & Not the Same

A Curriculum Module developed by Matthew A. Armfield from Deerfield High School for Northwestern University's Nanoscale Science and Engineering Center through the 2005 Research Experience for Teachers Program

NORTHWESTERN UNIVERSITY

Topic Overview

Content in a Nutshell

Allotropes are compounds that exist in forms with different chemical structures. Some common examples of allotropes are phosphorus (“white” or “yellow”, “red”, and “black / purple”), oxygen (O_2 and O_3) and finally carbon (diamond, graphite, fullerenes and carbon nanotubes, or CNTs).

The specific hybridization of carbon, and its bonding to surrounding atoms will determine which allotrope carbon will assume. Carbon with sp^3 hybridization will form a tetrahedral lattice, thus giving rise to diamond. Carbon with sp^2 hybridization will form either graphite (arranged in hexagonal sheets), buckminsterfullerene (60 carbon atoms forming a sphere), or carbon nanotubes (long hollow tubes of carbon) – depending on the conditions in which it is formed.

Diamond and graphite have been known since ancient times (the word diamond comes from the ancient greek, *adamas* meaning “impossible to tame”) but buckminsterfullerene and CNTs have only been discovered within the last twenty years, and are just beginning to be characterized.

Buckminsterfullerene, C_{60}, was discovered by Kroto, Smalley and coworkers in 1985, although its possible existence had been discussed by other chemists years earlier. For the first few years after its discovery, it was a laboratory curiosity. However, when it was discovered that macroscopic amounts of C_{60} were formed by heating graphite rods under carefully controlled conditions, research on this material took off. One of the first questions organic chemists asked about it was, “What are its chemical properties?” Since all of the carbons on buckminsterfullerene are sp^2 hybridized, C_{60} could be like benzene, C_6H_6, which is an aromatic molecule, or like ethylene, which is a typical alkene. Furthermore, since CNTs (which are also referred to as “buckytubes”) have the same hybridization as C_{60}, will these two chemicals react in similar fashion?

The applications for these new nanostructures are immense. Although no practical application for buckyballs have been developed yet, scientists are extremely excited about the potential uses of carbon nanotubes. These structures have a diameter between 1 and 10 nanometers (about 1000 times thinner than a human hair!), yet are 50 times stronger than steel. Carbon nanotubes are also structurally perfect, and this property gives rise to a whole host of other unique properties, such as unique electrical properties and high thermal conductivity.

Place in the Curriculum

The concepts of chemical bonding and elements of the periodic table are essential for any introductory chemistry course. Also, the notion of structure versus function is a fundamental concept in many different subject areas. This module extends the normal classroom discussion of ionic and covalent bonding into the realm of hybridization, organic chemistry and nanotechnology.

Students are expected to have a working knowledge of the basics of chemical bonding, the periodic table and general laboratory skills before beginning this module. Although not typically discussed in a first-year introductory chemistry course, an overview of hybridization would also be helpful.

This module, as written, is appropriate for a first-year introductory chemistry course. Depending on the level of students enrolled in the course, the difficulty level of this module is that of an honors or rigorous regular-level chemistry course. Furthermore, due to the inquiry-based nature of this module, and the laboratory experiments performed in Part Two, it is essential that an environment of collaboration and cooperation already established in the classroom, and students' laboratory skills are up to par.

If more emphasis and discussion is placed on Parts Two or Three, with supplemental lectures and teaching, this module would also be appropriate for a unit on organic chemistry or a unit on science, technology and society.

Learning Goals & Objectives

The overall **goal** of this curriculum module is for the student to understand the complex relationship between structure and function. This goal will be met through three different activities in this module, each with its own specific set of objectives:

Part I: Molecular Modeling

1. Recognize the major different chemical and physical properties of the four allotropes of carbon;
2. Construct a molecular model for each of these four molecules; and
3. Explain how the molecular structure of these four allotropes dictates their chemical and physical properties.

Part II: Chemical Reactivity

1. Determine if buckminsterfullerene behaves more like an aromatic compound, or an alkene; and
2. Compare the chemical reactivity between graphite, buckminsterfullerene and CNTs.

Part III: Practical Applications

1. Research the potential applications of carbon nanotubes to the scientific community and society; and
2. Present this information in poster format, and critique others' research at a research symposium.

Laboratory Activity: Student Version

Activity 1: Molecular Modeling of Carbon Allotropes

Introduction

Diamonds are valuable because of their extraordinary physical and chemical properties. Their hardness and light dispersion abilities make them a very coveted substance. *Graphite* is a substance that has a myriad of practical uses, such as the "lead" in your pencil. *Buckminsterfullerene,* usually referred to as "buckyballs", is a substance whose molecular structure resembles that of a soccer ball. Its structure was unlike anything seen before. Soon after, *carbon nanotubes* (CNTs), were discovered in 1991. CNTs are amazing tubes made from carbon that range from 1 to 12 nanometers in diameter (the diameter of 1 atom is approximately 0.1 nanometers), and are currently under intense investigation in the field of nanotechnology.

What is so remarkable about these four substances is that they are all made of the same element: carbon. Why then do these materials, which are all made of pure carbon, behave so differently?

Objectives

At the end of this lab activity, you should be able to…

1. Recognize the major different chemical and physical properties of the four allotropes of carbon;
2. Construct a molecular model for each of these four substances; and
3. Explain how the molecular structure of these four allotropes dictates their chemical and physical properties.

Advance Preparation

Please answer the following questions before you begin this lab activity:

1. What is an *allotrope*? Besides the ones mentioned above, what other allotropes exist?
2. Who discovered buckminsterfullerene? Why did its discoverer give this molecule this particular name?
3. What does the prefix "nano" mean? Use this information to describe what a "nanotube" is.

Procedure

Part A: Physical & Chemical Properties

1. In your laboratory notebook, make a table with the following four headings: diamond, graphite, buckminsterfullerne (C_{60}), and carbon nanotubes (CNT).
2. Underneath each column, list all of the properties of each substance you can think of off the top of your head. Brainstorm with your laboratory group to come up with a good list. If you wish, study the variety of images of these four allotropes on my website.
3. Using the internet or other reliable research sources, determine the following properties for each of the four allotropes. Make sure you also record the internet sites where you found this information. *NOTE: You might not be able to find all of the information for each of the four. If this is the case, make a good estimate of its value compared to the other allotropes you've researched.*
    a. Color
    b. Density (g/cm^3)
    c. Specific gravity
    d. Hardness (Moh's scale)
    e. Melting Point
    f. Boiling Point
    g. Electrical conductivity
    h. Hybridization
    i. Crystal structure and/or shape
4. If you were not able to find this information for a particular allotrope, what does this tell you about the knowledge scientists have concerning these allotropes?

Part B: Molecular Structures

Now that you have explored some of the most easily observable properties of these allotropes, you will use the molecular modeling kits in front of you to create molecular representations of each of these four carbon allotropes.

1. Each member of your laboratory group will create one of the four allotropes. Decide on which allotrope you will build (diamond, graphite, buckminsterfullerene, and a CNT).
2. Using the molecular modeling pieces and the model building guide provided, construct your model.
3. When you think you are finished, show your model to your instructor. Upon approval, accurately draw your representation in your laboratory notebook.

Analysis

1. Discuss the differences in chemical bonding between the four allotropes of carbon. Include in your discussion descriptions of the allotrope's hybridization and the specific bonding that is occurring between its surrounding atoms.
2. Examining your molecular representations of diamond and graphite, explain why diamond is one of the hardest materials known (the "ultimate abrasive"), and graphite is one of the softest (i.e. it's an excellent lubricant).
3. *Tensile strength* is defined as the greatest longitudinal stress a substance can bear without tearing apart (i.e. think "tug-of-war"). In 2000, single-walled carbon nanotubes were reported to have a tensile strength of approximately 62 GPa. In contrast, high carbon steel (an alloy of iron and carbon) has a tensile strength of approximately 1.2 GPa.
    a. Describe the differences in bonding between a tube of steel and a carbon nanotube.
    b. Use this information to explain the differences in tensile strength between a CNT and steel.
4. Explain, using your findings from this activity, how the structure of a substance is just as important in determining the substance's physical properties as its molecular composition (what it's made of).
5. How would the results of this activity be different if the properties of a substance were *independent* of form?

Activity 1: Molecular Modeling of Carbon Allotropes

Laboratory Activity: Teacher Notes

Major Chemical Concepts

Allotropy is the property possessed by certain substances of existing in forms with different chemical structures; the various forms are known as *allotropes*. Depending on the substance, allotropes can have vastly different physical and chemical properties, even though they are composed of the same element.

Level

This activity can be done with first year regular-level or honors-level chemistry students.

Expected Student Background

Students should know how and why covalent bonds form and the differences between single and double bonds. Students should be familiar with some basic physical properties of elements (density, melting point/boiling point, hardness, etc…) or have access to resources to find out what these properties mean. Also, students should know how to search and find reliable information using the internet.

Time

Depending on the level of teacher guidance and pre-laboratory preparation, this activity can range from 30 minutes to 90 minutes.

Safety

There are no safety precautions for this activity.

Materials (for 24 students working in groups of 4)

- 6 computers connected to the internet
- Orbit Molecular Model Kits (all can be obtained from Indigo Instruments: http://www.indigo.com)
    - 6 Diamond models
    - 6 C_{60} Buckminsterfullerene models
    - 6 Buckytube models
    - 6 Graphite models
- 6 samples of graphite rock (*recommended*)

Pre-Laboratory Discussion

Review the advance preparation questions before beginning the laboratory:

1. Allotropes are compounds that exist in forms with different chemical structures. Other allotropes besides carbon are phosphorus and oxygen.
2. Harold Kroto, Robert Curl and Richard Smalley discovered buckminsterfullerene in 1985. They gave it this name in honor of Richard Buckminster Fuller, who popularized the geodesic dome.
3. The prefix "nano" means 10^{-9} of something. Nanotubes are tubes that have a diameter of around 10^{-9} nanometers, in other words, they are *very* small.

During the Activity

Students might need some guidance to determine the properties of the various allotropes. Some recommended sites are as follows (accessed July 2005):

1. Wikipedia – http://en.wikipedia.org
2. Properties of Diamonds – http://newton.ex.ac.uk/research/qsystems/people/sque/diamond/
3. Diamonds – http://ist-socrates.berkeley.edu/~eps2/wisc/Lect6.html
4. Graphite Properties Page by John A. Jaszczak – http://www.phy.mtu.edu/~jaszczak/graphprop.html
5. The World of Carbon – http://invsee.asu.edu/nmodules/Carbonmod
6. Properties of Carbon and C60 – http://www.creative-science.org.uk/propc60.html
7. Fullerene, C60 - http://www.chemicalland21.com/arokorhi/industrialchem/organic/FULLERENE%20C60.htm
8. Physical Properties of Carbon Nanotubes – http://www.pa.msu.edu/cmp/csc/ntproperties/

Students might need help in constructing their molecular models. It might help to have a sample model to show as an example.

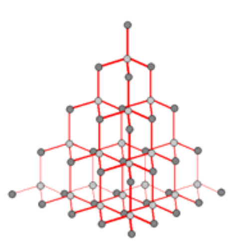
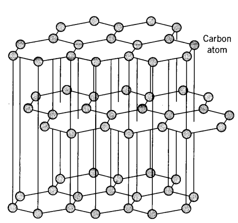
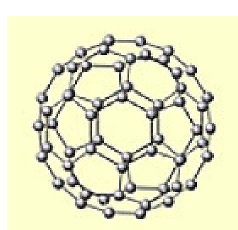
Anticipated Results

Part A: Physical & Chemical Properties

	DIAMOND	GRAPHITE	C_{60}	CNTs
Color	Colorless[1]	Steel black to grey[1]	Black solid / Magenta in solution	black
Density (g/cm^3)	3.515[2,5]	1.9-2.3[5]	1.69[5]	1.33-1.4[8]
Specific Gravity	3.52[3]	2.2[4]	1.7-1.9[7]	***2***
Hardness (Moh's Scale)	10[1]	1-2[1]	***1-2***	***1-2***
Melting Point (°C)	3550[5]	3652 – 3697[5]	>800 (sublimes)[6]	***Similar to graphite***
Boiling Point (°C)	4827[5]	4200[5]	n/a	n/a
Electrical Conductivity	Insulator[1]	Conductor[1]	Semi-conductor[6]	Conductor to semi-conductor[1]
Hybridization	sp^3 - tetrahedral[1]	sp^2 – trigonal planar[1]	sp^2 – trigonal planar	sp^2 – trigonal planar[1]
Crystal Shape and/or Structure	Cubic[1]	Tabular[1]	Truncated icosahedron[1]	Cylindrical[1]

Superscripts refer to the above websites where the information was gathered. Answers in purple bold indicate values estimated from known values of other allotropes.

Part B: Molecular Modeling

DIAMOND	GRAPHITE	C_{60}	CNTs
			

Post-Laboratory Activities

1. Have students compare their models between groups.
2. Hold a large group discussion as to how the models of the different allotropes compare.
3. Review the concepts of hybridization and VSEPR theory to help them with their data analysis.

Assessing Laboratory Learning

1. Have students hold a discussion about the analysis questions, or have individuals (or groups) turn in their answers for credit.
2. Show them molecular representations of each allotrope and ask them to relate specific properties of these substances to their structure.
3. Write a short essay explaining why substances with the exact same chemical composition can have a wide variety of chemical and physical properties.
4. Give them a list of chemical properties (some of which they might not have seen before…) and have them match these properties to the substance that holds this property.

Answers to Laboratory Analysis

1. Each of the four allotropes has a different form of bonding. Carbon atoms in a sample of diamond exhibit sp^3 hybridization and form a network covalent lattice of tetrahedral carbon atoms. Although the carbon atoms of graphite, buckminsterfullerene and CNTs all display sp^2 hybridization, and their bonding patterns are different. Graphite forms strong, covalent bonds in only 2 dimensions, and forms weak van der Walls interactions between the sheets. The carbon atoms in buckminsterfullerene are all covalently bonded to one another, but in a CNT, these carbons are extended to form a tube, rather than a ball.
2. All of the carbon atoms in a diamond molecule are covalently bonded to one another. Therefore, this molecule is extremely strong and rigid. On the other hand, although graphite has double bonds between some of its atoms, only weak van der Walls forces exist between the sheets of covalently bonded carbons. These weak forces are easily broken, and as a result, sheets of graphite can flake off, and as a result, graphite is quite soft.
3.
    a. No formal bonding (i.e. ionic or covalent) exists between atoms of steel (an alloy of iron and carbon), only *metallic bonding*. Electrons flow between all of the atoms in a sample of steel, but the individual atoms are not held together by any strong bonding force, either electrostatic or physical. The atoms in a carbon nanotube, on the other hand, are all covalently bonded to one another.

    b. The differences in tensile strength are due to the relatively weak forces holding the atoms of steel together, and the strong covalent bonds found in a carbon nanotube.

4. All of the substances in this activity had the exact same molecular composition: they were all made of carbon. However, they all had different molecular structures, and as a result, they all have different physical properties.
5. If function was purely based on form, then all of their physical properties would be identical.

Laboratory Activity: Student Version

Activity 2: Chemical Reactivity of Carbon Allotropes

Introduction

Buckminsterfullerene, C_{60}, was discovered by Harold W. Kroto in 1985, although its possible existence had been discussed by other chemists years earlier. It is an example of an *allotrope* of carbon. Allotropes are compounds that exist in forms with different chemical structures, such as diamond and graphite. For the first few years after its discovery, it was a laboratory curiosity. However, when it was relatively easy to manufacture pure samples of C_{60}, research on this intriguing molecule took off.

Buckminsterfullerene is an example of a completely new class of organic compound. One of the first questions organic chemists asked about it was "What are its chemical properties?" Since all of the carbons on buckminsterfullerene are sp^2 hybridized, C_{60} could be like benzene, C_6H_6, which is an aromatic molecule, or like ethylene, C_2H_4, which is a typical alkene. The double bond in an alkene is reactive, and reacts with many chemicals, changing the hybridization of the double bond carbons from sp^2 to sp^3. Aromatic molecules, on the other hand, are very stable. The three double bonds in a benzene ring lead to great stability and much lower reactivity. Thus, reagents that react with ordinary alkene double bonds tend to leave benzene alone.

We will investigate the properties of buckminsterfullerene by comparing its reactivity with that of a typical alkene, cyclohexene, and a typical aromatic molecule, napthalene. Furthermore, you will see how easily you can change one of the physical properties of buckminsterfullerene simply by changing the size of the molecule.

Objectives

At the end of this lab activity, you should be able to…

1. Determine if buckminsterfullerene behaves more like an aromatic compound, or an alkene; and
2. Compare the chemical reactivity between graphite, buckminsterfullerene and CNTs.

Safety

- Laboratory goggles and aprons and nitrile gloves (not latex) must be worn at all times throughout this laboratory.
- Perform the reactions in a well ventilated room, or underneath a fume hood. Avoid breathing the vapors of the chemicals used.
- All chemicals used during this activity must be properly disposed of. Do not pour anything down the sink.

Advance Preparation

Observe figures 1-3 to the right, and compare the chemical structures of buckminsterfullere (figure 1), naphthalene (an aromatic compound, figure 2) and cyclohexene (an alkene, figure 3). Predict which class of chemicals, aromatics or alkenes, buckminsterfullerene will behave most like. Explain your reasoning.

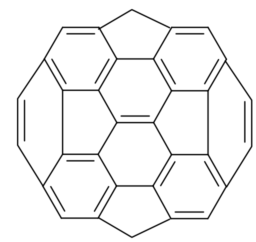


***Figure 1** – Lewis structure for a partial molecule of C_{60}*

Procedure

Part A: Bromination

1. You will be performing this reaction four times, each with a different starting chemical:
    a. buckminsterfullerene solution "A"
    b. alkene solution "A"
    c. aromatic solution "A"
    d. control solution "A"

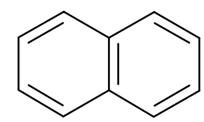


***Figure 2** – Lewis structure for a molecule of napthalene*

2. Add 1 mL of your solution to a 50 mL Erlenmeyer flask or large test tube. Observe the initial color of your solution.
3. To this solution, add 2.5 mL of *Winkler's Solution* and 2.5 mL of hydrochloric acid. Immediately stopper the flask.

    CAUTION: this reaction produces bromine gas (Br_2) which is toxic. Make sure you stopper the flask to avoid inhaling the vapors that are produced.

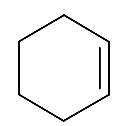


***Figure 3** – Lewis structure for a molecule of cyclohexene*

4. Gently swirl the flask and observe the color of your solution. Compare your results with your laboratory group. Record your observations in your laboratory notebook.
5. After five minutes, add 2 mL of $Na_2S_2O_3$. This will eliminate of any excess bromine present in the flask.
6. Repeat steps 2-5, but use a different allotrope of carbon: either nanotube solution "A" or graphite solution "A". Perform both reactions if time permits.

Part B: Permanganate Test for Alkenes

7. Once again, you will be performing this reaction four times, each with a different starting chemical. *Make sure you do not mix up solution "A" with solution "B". They are very different!*
    a. buckminsterfullerene solution "B"
    b. alkene solution "B"
    c. aromatic solution "B"
    d. control solution "B"
8. Add 1 mL of your solution to a test tube.
9. To this test tube, add 1 mL of acidic potassium permanganate ($KMnO_4$), gently swirl for one minute.

10. Compare your results with your laboratory group, and record your observations in your laboratory notebook.
11. Repeat steps 2-4, but once again, use a different allotrope of carbon: either nanotube solution “B” or graphite solution “B”. Perform both reactions if time permits.

Part C: Complexation Reaction

1. Add 1 mL of buckminsterfullerene solution “B” to a test tube. Record your observations.
2. To this test tube, add, dropwise, 5-8 drops of *o*-dimethoxybenzene. Record your observations.
3. To this solution, add 2 mL of toluene. Once again, record your observations.
4. Repeat steps 2-3, but instead of using buckminsterfullerene solution “B”, use nanotube solution “B” or graphite solution “B”. Perform both reactions if time permits.

Analysis

1. Describe why a molecule of buckminsterfullene could behave as an aromatic compound, or as an alkene.
2. According to your data, a molecule of buckminsterfullerene behaves most like what class of chemicals: an aromatic or an alkene? Justify your conclusion with data you obtained from the laboratory.
3. Although all three allotropes tested in this laboratory are made of pure carbon, do they all have the same reactivity? What does this tell you about the relationship between a chemical’s composition, structure and function?

Activity 2: Chemical Reactivity of Carbon Allotropes

Laboratory Activity: Teacher Notes

Major Chemical Concepts

Since its discovery in 1985, buckminsterfullerene has been extensively studied by scientists all over the world. Many of these experiments demonstrate a linkage between inorganic and organic chemistry, in that the new modification of "inorganic" carbon shows reactions typical of organic chemistry.

Level

This activity can be done with first year regular-level or honors-level chemistry students.

Expected Student Background

Students should be familiar with the concept of allotropy, and basic organic chemistry (alkanes, alkenes, alkynes and aromatic molecules). Students should be able to make detailed observations and perform laboratory experiments following safe protocol.

Time

One 55-minute laboratory period should be ample time to complete all three parts of this lab. If time and materials are short, one could choose to do this in groups of four rather than groups of two as written.

Safety

- Laboratory goggles and aprons are a necessity while performing this lab and nitrile gloves (***not*** latex gloves) are required.
- Experiments should be performed in a well-ventilated classroom or underneath a fume hood. Precautions should be taken to avoid inhaling the organic vapors produced.
- Although there is no evidence of poisonous properties, the fullerenes should be handled with care. Contact with eyes or skin should be avoided.
- Tetrachloroethylene is a highly toxic and volatile chemical that can easily be absorbed through the skin. Proper handling and disposal is necessary when using this chemical.

Materials (for 24 students working in groups of 2)

Part A

- 20 mL of each of the following test solutions "A":
  - C_{60} in tetrachloroethylene (0.5 mg/mL)
  - cyclohexene (5% by volume in tetrachloroethylene)
  - naphthalene (5% by volume in tetrachloroethylene)
  - tetrachloroethylene
- 100 mL of Winkler's Solution (0.556 g $KBrO_3$ and 2.0 g KBr in 100 mL distilled water)
- 100 mL of 2 *M* hydrochloric acid (HCl)
- 100 mL of 1 *M* sodium thiosulfate ($Na_2S_2O_3$)
- 48 Erlenmeyer Flasks, 50 mL or large test tubes
- 48 rubber stoppers, size 1
- Nitrile gloves, 1 box

Part B

- 20 mL of each of the following test solutions "B":
  - C_{60} in toluene (0.3 mg/mL)
  - cyclohexene (5% by volume in toluene)
  - naphthalene (5% by volume in toluene)
  - toluene
- 50 mL of acidic potassium permanganate solution (0.01% in 0.1 *M* H_2SO_4)
- 48 test tubes, 13 x 100 mm
- 48 stoppers, size 0

Part C

- 20 mL of C_{60} in toluene (0.3 mg/mL)
- 20 mL of *o*-dimethoxybenzene
- 100 mL toluene
- 48 test tubes, 13 x 100 mm
- 48 stoppers, size 0

NOTE: Sigma-Aldrich sells both buckyballs (product number 483036) and medium quality CNTs (product number 519308) at reasonable prices. If nanotechnology commercial or research institutions exist in your area, you might try asking these places to donate samples for educational use.

Pre-Laboratory Discussion

Review (Think-Pair-Share) people's predictions and explanations before beginning the activity. It is not important for them to correctly predict what class of chemicals it will behave like, however, it is important for them to *explain* their reasoning using the chemical structures of the three compounds.

Anticipated Results

Part A: Bromination

	C_{60}	Napthalene	Cyclohexene	Tetrachloro-ethylene
Initial				
Final				

	C_{60}	Graphite	Carbon Nanotubes
Initial			
Final			

Part B: Permanganate Test for Alkenes

	C_{60}	Napthalene	Cyclohexene	Tetrachloro-ethylene
Initial				
Final				

	C_{60}	Graphite	Carbon Nanotubes
Initial			
Final			

Part C: Complexation Reaction

	C_{60}	Graphite	Carbon Nanotubes
Initial			
Final			

Answers to Analysis Questions

1. A molecule of buckminsterfullerene is structurally similar to an aromatic compound because of the numerous conjugated double bonds it contains, and as an alkene, due to the presence of these double bonds.

2. According to the data acquired in the lab, a molecule of buckminsterfullerene behaves most like an alkene. This is shown with the bromination reaction, as the final color for both the C_{60} solution and the alkene solution were similar, as well as with the potassium permanganate reaction.

3. The chemical reactivity for all of the carbon allotropes tested in this laboratory was different. This indicates that even if two or more substances have similar chemical composition, the form or structure that the substance has is just as important in determining its chemical reactivity (its function).

Activity 3: Practical Applications of Carbon Nanotubes

Research Activity: Student Version

Introduction

Discovered in 1991 by Sumio Iijima of NEC Corporation, carbon nanotubes (CNTs) can be considered an exotic variation of common graphite. The electronic and mechanical properties of this tubular molecule has caused many a researcher to take interest. Through extensive research, scientists now attribute many intriguing properties to this unique substance, such as, super strength, low weight, stability, flexibility, good heat conductance, large surface area and a wide range of interesting electronic properties.

These unique properties have led scientists to speculate a host of practical applications for both future scientific research and real-world uses. For example, CNTs could be used to help paint adhere to car parts, and fantasies such as earth-tethered satellites could become a reality with fibers made of CNTs. Remarkably, some technologies have already been developed and are now being tested, such as using CNTs in televisions as a replacement for traditional cathode ray tubes.

You will be working in groups of four to research a potential use for carbon nanotubes in either the scientific community or in society. You will then present your research to your classmates at a poster session in a few weeks. Get ready to dive into the forefront of current chemical research!

Objectives

At the end of this lab activity, you should be able to…

1. Research the potential applications of carbon nanotubes to the scientific community and society; and
2. Present this information in poster format, and critique others' research at a research symposium.

Part One: What ARE Carbon Nanotubes?

Read the article "Tantalizing Tubes" from the June 2000 issue of *Scientific American*, and the table from the article "Nanotubes for Electronics" from the December 2000 issue of *Scientific American*. This will give you a good overview of CNTs, and a little information on their possible applications. When you are finished reading, think about, and then answer, the following questions in your laboratory notebook:

1. A report for *The Economist* stated, "The only industry the buckyball has really revolutionized is the generation of scientific papers." What did he mean by this statement?
2. Carbon nanotubes can either behave as metals (and conduct electricity) or as semi-conductors. What causes this difference in electrical conductivity?
3. What are two promising applications for carbon nanotubes that you find most interesting?
4. What are two limitations of the use of CNTs in technology and industry?

Start brainstorming with your group as to what you might want to research. The ideas presented in these articles are just a beginning – there are many more possible applications. Try researching in scientific magazines such as *Scientific American* or *Discover*, or online (even a general site such as Wikipedia gives a wealth of good information) to find a topic that interests you.

Part Two: Begin Your Research

You and your research team will chose **one** application of carbon nanotubes and research what it is, how it could be used and current limitations of this technology. Your research should be broken down into these three general areas:

1. **General Overview.** This section should provide sufficient background information for anyone outside the field of nanotechnology to understand your specific research topic. Consider these questions when writing this section:
   a. What is nanotechnology?
   b. What are carbon nanotubes? (history, chemical composition, structure, chemical and physical properties, possible uses, etc…)
   c. How do carbon nanotubes relate to nanotechnology?
2. **Specific Application.** You need to specifically focus on your chosen application during this section of your report. This section should address the following points:

a. Report on the science behind your specific application. How does it work? How do nanotubes help this technology perform its job?

b. Discuss how this specific CNT technology could be used to help advance science and/or society.

c. Who is currently working on this technology? What institution or company is developing this idea? Will it be available to the public, or mainly used in research?

3. **Advantages & Current Limitations.** Some questions to think about:

a. Why do scientists want to develop this application? What benefits will it have over current technologies?

b. Not all advances in technology are 100% beneficial. Are there any *disadvantages* to these applications? If so, what are they? What can be done to address these disadvantages?

c. What is preventing the use of this application in mainstream society at this time? (Think cost, feasibility, current limitations in technology, materials, etc…)

Remember references! A part of your overall grade for this project will be your reference list. Therefore it is important to remember where you got all of your information. Are your sources reliable? Does any of your information come from "non-credible" websites? Is your information current? You will need ***at least*** five (5) references total, and two of those references must be from a print resource. *Online magazines, newspapers, journals* ***do*** *meet this requirement, provided you reference them as print, rather than an online source.*

Part Three: Present Your Research

As you learned at the beginning of the year, there are many ways that scientists present their research findings to the public: journal publications, talks, poster sessions and online, to name a few. For this project, you will present your research in the form of a scientific poster that will be reviewed by your peers (and me!) at a research symposium.

Your poster should follow the basic conventions for reporting scientific research. However, instead of the traditional research headings ("Methods", "Results", etc…) your poster should have the following section headings:

1. General Overview
2. Specific Application
3. Advantages & Current Limitations
4. References

A rubric for this part of the project is on the back of this handout.

Grading Rubric: Practical Applications of Carbon Nanotubes

Content: *General Overview (10 points sliding scale, criteria listed below. Zero points given if the section is missing.)*					
0 ← 1	**2 — 3**	**4 — 5**	**6 — 7**	**8 — 9 → 10**	Total:
Two or more subtopics missing or extremely inaccurate. Very little effort shown to complete requirements.	One subtopic is missing or grossly incomplete; inaccurate information reported throughout section.	Some incorrect information is included, or not enough is included to completely explain the topic.	Too much information is included. Information is correct, but confusing and/or unclear.	Sufficient information is provided, all required points are addressed, & provides an accurate overview of the general topic.	
Content: *Specific Application (10 points sliding scale, criteria listed below. Zero points given if the section is missing.)*					
0 ← 1	**2 — 3**	**4 — 5**	**6 — 7**	**8 — 9 → 10**	Total:
Two or more subtopics missing or extremely inaccurate. Very little effort shown to complete requirements.	One subtopic is missing or grossly incomplete; inaccurate information reported throughout section.	Some incorrect information is included, or not enough is included to completely explain the topic.	Too much information is included. Information is correct, but confusing and/or unclear.	Sufficient information is provided, all required points are addressed, & provides an accurate overview of the general topic.	
Content: *Advantages & Current Limitations (10 points sliding scale, criteria listed below. Zero points given if the section is missing.)*					
0 ← 1	**2 — 3**	**4 — 5**	**6 — 7**	**8 — 9 → 10**	Total:
Two or more subtopics missing or extremely inaccurate. Very little effort shown to complete requirements.	One subtopic is missing or grossly incomplete; inaccurate information reported throughout section.	Some incorrect information is included, or not enough is included to completely explain the topic.	Too much information is included. Information is correct, but confusing and/or unclear.	Sufficient information is provided, all required points are addressed, & provides an accurate overview of the general topic.	

Poster: *Organization (7 points maximum, Specified number of points awarded for each of the following…)*				
1	**1 or 2**	**1 or 2**	**1 or 2**	Total:
Poster is organized in vertical columns *(sufficient space between columns leaves no doubt about where one column ends & another begins)*	Sequence of the poster is easy to follow using visual clues provided *(clues may include numbers, letters, arrows, headings, etc…)*	Text is simple and large enough to be read from a minimum of four feet away *(a standard, easy to read text is used)*	Content is efficiently placed throughout the poster; large amounts of blank space is avoided or content is not crammed together	

Rubric continued on back…

Poster: *Presentation (8 points maximum, Specified number of points awarded for each of the following…)*					
1 All titles and subtitles are clear and enhance the readability of the poster	**1** All text is typed and pictures/illustrations are neat and (when appropriate) in color *(anything done by hand is inappropriate)*	**1 or 2** Relevant graphics support the information provided *(use graphics, illustrations and/or figures whenever possible)*	**1 or 2** Color is used to emphasize or link words and images *(color changes serve a purpose)*	**1 or 2** Artistic elements of the poster are subtle and do not distract from the message of the poster *(scientific posters present information clearly)*	Total:

Presentation: *(10 points sliding scale, criteria listed below)*					
0 ← 1	**2 3**	**4 5 6**	**7 8**	**9 → 10**	Total:
Little knowledge or no knowledge about the topic, cannot answer simple questions. Poor presentation skills	Average knowledge of the topic, answers a few questions accurately. Poor presentation skills	Good knowledge of the topic but doesn't answer all questions correctly. Presentation skills could use improvement	Good working knowledge of the topic and answers questions accurately. Presentation skills could use improvement	Excellent working knowledge of the topic, answers all questions accurately and very good presentation skills	

References: *(5 points sliding scale, criteria listed below. Zero points given if the section is missing.)*					
1	**2**	**3**	**4**	**5**	Total:
Less than 5 references.	At least 5 references, including 2 print sources, are not cited correctly. Two print sources are missing.	At least 5 references, including 2 print sources, are not cited in APA format or a few errors are present.	At least 5 references, including 2 print sources, are correctly cited in APA format. Pictures/illustrations are *not* cited.	At least 5 references, including 2 print sources, are correctly cited in APA format. All pictures/illustrations are cited.	

Penalties: *(Maximum amount of points deducted listed above penalty)*					
(-5) Spelling errors *(1 point penalty each, up to five)*	**(-5)** Incorrect grammar, usage and/or punctuation *(1 point penalty each, up to five)*	**(-10)** Laziness *(lack of participation or focus during designated work time)*	**(-50)** Plagiarism *(see me if you have questions as to what is/isn't considered plagiarism)*	**(-25)** Not completed on time *(5 points per day)*	Total:

Comments:	***FINAL SCORE:*** *out of 60*

Research Activity: Teacher Notes

Activity 3: Practical Applications of Carbon Nanotubes

Major Chemical Concepts

Carbon nanotubes, unlike buckyballs, have the potential to be quite useful in scientific and commercial products, from super-strong clothing to test tubes with a diameter of 10-12 nanometers. As research into carbon nanotubes continues, more and more applications of these amazing molecules will be discovered.

Level

This activity can be done with first year regular-level or honors-level chemistry students.

Expected Student Background

Students should know what carbon nanotubes are, and some of their unique properties. Also, they should know how to research advanced scientific information, as well as interpret science-rich information sources (such as *Scientific American, New Scientist* or *Discover* magazine). Depending on how you wish to evaluate this section of the module, the students should know how to create an effective scientific poster, and peer review another group's research.

Time

This activity is best performed with one to two days of in-class work. It is likely that additional outside research, writing and poster building will be necessary to complete this project.

Safety

There are no safety precautions for this activity.

Materials (for 24 students working in groups of 4)

- 6-12 computers connected to the internet
- Copies of the two articles referenced in the activity:
  - Mirksy S. (June 2000) Tantalizing Tubes. *Scientific American*. 40-42.
  - Collins PG, Avouris P. (Dec 2000) Nanotubes for Electronics. *Scientific American*. 68.
- Examples of scientific posters

Pre-Research Discussion

Review the questions from the journal readings before allowing the students to begin their research:

1. No practical applications have yet to be discovered for buckyballs. Scientists have discovered a lot about their properties (therefore producing a number of scientific papers on the subject) but they have yet to apply this knowledge to any practical use.
2. Hamada and Dresselhaus found that if a row of carbon hexagons in the carbon nanotube's long axis was straight, the CNT would behave like a metal and conduct electricity. If a line of hexagons formed a helix, however, the tube would behave as a semiconductor.
3. Applications would include: transistors & diodes, field emitters for flat-panel displays, cellular-phone signal amplifiers, ion storage for batteries, materials strengthener, chemical and genetic probes, mechanical memory for computers, nano-laboratory equipment, super-sensitive sensors, and super sensitive microscopes.
4. Limitations would include: cost, lack of technology, unknown knowledge about nanotubes, etc…

During the Activity

Students might need some guidance to find various technologies for carbon nanotubes. Some sites and/or articles that could be of guidance (websites accessed July/August 2005):

- Fabrics
  - *Super Fibers: Nanotubes make tough threads:* http://www.phschool.com/science/science_news/articles/super_fibers.html
- Space elevator
  - *Going Up*: http://www.discover.com/issues/jul-04/cover/
- Nano-sized test tubes
  - *Smallest "test tube" scoops world record:* http://www.newscientist.com/article.ns?id=dn6710
  - Britz DA, et al. Chemical reactions inside single-walled carbon nano test-tubes. *Chem. Commun.*, 2005 (1): 37-39.
- Field emission (nano-CRTs)
  - *Carbon nanotubes used in computer and TV screens:* http://www.newscientist.com/channel/mech-tech/nanotechnology/mg18625006.800
- Nanobrushes
  - *World's smallest toothbrush scrubs capillaries clean:* http://www.newscientist.com/channel/mech-tech/nanotechnology/dn7507
  - Cao A, et al. Multifunctional brushes made from carbon nanotubes. *Nature Mat.* 4, 540-545 (01 Jul 2005)

- Medicine (fighting disease & cancer):
    - *Nanotubes get to grips with the 'burger bug':* http://www.newscientist.com/channel/mech-tech/nanotechnology/mg18524876.100
    - Gu L, et al. Single-walled carbon nanotubes displaying multivalent ligands for capturing pathogens. *Chem. Commun.,* 2005: 874-876.
    - *Scientists develop nanotech-laser treatment that kills cancer cells without harming healthy tissue:* http://www.biologynews.net/archives/2005/08/02/scientists_develop_nanotechlaser_treatment_that_kills_cancer_cells_without_harming_healthy_tissue.html
- Medicine (tissue repair/rebuilding)
    - *Nanotubes inspire new technique for healing broken bones:* http://www.biologynews.net/archives/2005/07/08/nanotubes_inspire_new_technique_for_healing_broken_bones.html
- Conductive plastics (polymers)
- Electrical conductors
- Computer memory
- Energy storage

Post-Laboratory Activities

1. Conduct a "research symposium" displaying their work. Have groups set up their posters throughout the classroom, and have students walk about the room taking notes on a few projects.
2. Give students a list of project summaries before presenting their work. Have students develop questions for other groups based on the 2-3 sentence summaries. During the research symposium, have the groups evaluate how well they answered their question. The teacher can also evaluate the quality of the question asked.
3. Posters should be displayed throughout the classroom or school for a period of time to showcase their work.

MATERIALS SCIENCE_NANOENGINEERING

Tantalizing Tubes

Hype aside, applications for carbon nanotubes progress—slowly

If good things come in small packages, then the tiniest packages should harbor the best things. Such is the thinking surrounding carbon nanotubes, a name that reflects their nanometer-scale dimensions. Discovered in 1991 by Sumio Iijima of NEC Corporation, carbon nanotubes are an exotic variation of common graphite. The tubular structure imparts mechanical and electronic properties that have raised the eyebrows of dozens of researchers at universities and commercial concerns around the world. The short list of attributes includes super strength, combined with low weight, stability, flexibility, good heat conductance, large surface area and a host of intriguing electronic properties.

The possibilities have led to breathless accounts of existing or potential real-world applications. For example, articles have hailed a company's use of alleged nanotubes as polymer additives to promote electrostatic adhesion of paint on car parts; the carbon in question is actually a grosser graphite that forms long fibrils. Other press reports have noted that nanotubes could be the fiber that finally makes earth-tethered satellites possible. Considering that the longest-known nanotubes are on the order of one millimeter, thoughts of a 35,800-kilometer-long nanotube rope are still a bit premature. These exaggerations aside, researchers have begun understanding and even exploiting nanotubes, particularly in electronics and in materials science.

Carbon nanotubes are descendants of buckminsterfullerene, or "buckyball," the soccer-ball-shape molecule of 60 carbon atoms. Despite the initial enthusiasm for applications, the roundest of round molecules has yet to see commercialization. As one wag in *The Economist* put it, "The only industry the buckyball has really revolutionized is the generation of scientific papers." Most research into applications has gravitated to the nanotubes, composed of hexagons of carbon atoms and looking very much like a miniature version of rolled-up chicken wire. (In reality, the tubes form not by furling sheets of graphite but by the self-assembling propensity of carbon atoms for knitting together, like yarn making a sweater sleeve, under various sets of extreme conditions.)

Shortly after nanotubes were discovered, Noriaki Hamada of NEC and Mildred S. Dresselhaus of the Massachusetts Institute of Technology independently uncovered an unusual twist, literally. They calculated that if a row of hexagons going down the tube's long axis were straight, the tube should behave as a metal and conduct electricity. If a line of hexagons formed a helix, however, the tube should act as a semiconductor. Both predictions were ultimately confirmed.

The electronics potential has become the most ballyhooed application for carbon nanotubes, in large part because silicon's future may be less bright than its past. "It is predicted that in 10 years or so, there may be bottlenecks appearing in the further improvement of silicon devices," explains Phaedon Avouris, manager of the nanoscale science and technology group at the IBM Thomas J. Watson Research Center. Continuing miniaturization of silicon components and fine control of electronic properties at smaller scales may soon pose intractable problems. So the electronics industry has begun looking for workable alternatives [see "Computing with Molecules," by Mark A. Reed and James M. Tour, on page 86]. "One of the possibilities is to base technology on a completely different element," Avouris states. "And in that case, carbon is the best bet." As the basic unit of organic chemistry, carbon is extremely well understood, a notion that comforts many researchers.

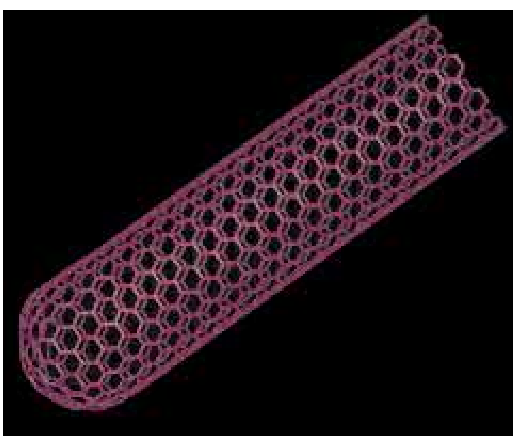
The past couple of years have seen promising demonstrations in carbon nanotube electronics. In 1998 both Avouris and Cees Dekker of the Delft University of Technology in the Netherlands showed that a single nanotube could act as a transistor. Last year, with Leon Balents of Lucent Technologies, Dekker reported that a single nanotube, with a natural junction where a straight section joined to a helical section, behaved as a rectifying diode—a half-transistor in a single molecule. Avouris has shown that the current flowing through a semiconducting nanotube can be changed by more than five orders of magnitude. "So," he observes, "it's a good switch."

Such virtuosity has electronics people understandably excited—but the road to sophisticated nanotube devices will be a long one. The work by Dekker and Avouris involves so-called single-wall nanotubes. "If you're going to make circuits, you have to organize the tubes," explains Thomas W. Ebbesen of the Nanostructure Laboratory at Louis Pasteur University in Strasbourg, France. "And every tube has a different property, depending on diameter and helicity. You can't even selectively grow one tube or another now." These challenges mean that development is a long way from reality. The only techniques currently available for bulk production form a mass of mixed types, including tubes within tubes, called multiwalled nanotubes, which have less well defined characteristics. For delicate electronics experiments, single-walled tubes of specific helicities must be painstakingly mined.

Fortunately, not all electronic applica-

Some Possible Uses for Carbon Nanotubes

- Transistors and diodes
- Field emitter for flat-panel displays
- Cellular-phone signal amplifier
- Ion storage for batteries
- Materials strengthener



RICHARD E. SMALLEY *Rice University*

FLAT SCREEN using carbon nanotubes as the source of phosphor-exciting electrons may compete with LCDs in a few years.

COURTESY OF SAMSUNG ADVANCED INSTITUTE OF TECHNOLOGY

tions need to be so elegant. Even messy mixtures of multiwalled tubes are good at field emission—they emit electrons under the influence of an electrical field. And field emission is the force behind flat-panel displays. A deep-bellied television or computer monitor relies on a big gun to shoot electrons at the pixels of a phosphor screen, which light up as ordered. Alternatively, millions of nanotubes arranged just below the screen could take the place of the gun. "Each pixel gets its own gun," explains David Tománek, a physicist at Michigan State University.

Several firms around the world are trying to exploit the nanotube talent in flat-panel displays. Researchers at the Samsung Advanced Institute of Technology in Suwon, South Korea, led by Won Bong Choi, appear to be in the lead. "Last Christmas they had a nine-inch display, and I could see baseball players," Tománek relates. The prototype required half the power of conventional liquid-crystal displays, and the nanotubes appear to meet the 10,000-hour lifetime typically demanded of electronics components. Zhifeng Ren of Boston College has produced neat forests of multiwalled nanotubes directly on glass surfaces, showing the potential of growing nanotubes in place, with the screen as substrate.

The issue for displays then becomes the orderly operation of all those nanotubes. "You have the complexity of now needing a separate circuit for every single pixel," points out Philip G. Collins, also of IBM's nanoscale group. Experts in conventional electronics need to find solutions to these intricate wiring problems before nanotube displays can become commonplace.

CSIRO MOLECULAR SCIENCE

STARSTRUCK: Researchers with CSIRO, the Australian organization for scientific and industrial research, have demonstrated that they can lay down nanotubes in patterns. Such control is critical for applications like flat-panel displays.

Nanotubes emit electrons at a relatively low voltage, which translates to minimal power requirements, while maintaining high current densities. These characteristics encouraged Otto Z. Zhou, a physicist at the University of North Carolina at Chapel Hill working with colleagues at Lucent, to try to generate microwaves via nanotube field emission, with implications for wireless communications. Cellular phones typically send a weak signal to a local base station, where microwave amplifiers beef up that signal.

"In principle, you could make the base station smaller, with a longer working life, thanks to the stability of the nanotubes," Zhou says. "We have a prototype that generates microwaves, the first time that that has been demonstrated in an electron emission material."

The battery designers are also keeping an eye on nanotubes. Graphite can store lithium ions, the charge carriers for some batteries, but at a weighty price: six carbon atoms for every lithium ion. Researchers speculate that the geometry inherent in bundles of nanotubes allows them to accommodate more than one lithium per six carbons. "It would be nice if you could access both the inside and the outside of the cylinder," remarks John E. Fischer, a materials scientist at the University of Pennsylvania, referring to both the insides of carbon nanotubes as well as the gaps between tightly packed tubes. "That's the leitmotif that runs through all research using nanotubes for anode materials," he adds.

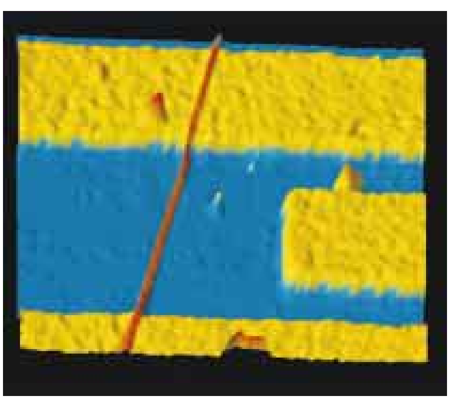
The holy grail in this world is probably hydrogen storage. The target for hydrogen capacity that would interest electric-car manufacturers is about 6.5 percent by weight, in whatever storage medium is used. Dresselhaus, writing in the *Materials Research Society Bulletin* last November, pointed out that various claims exceeding 6.5 percent have been difficult to reproduce. She notes that 4 percent by weight of hydrogen is the best figure available and that increasing it to the benchmark "represents a significant technological future challenge."

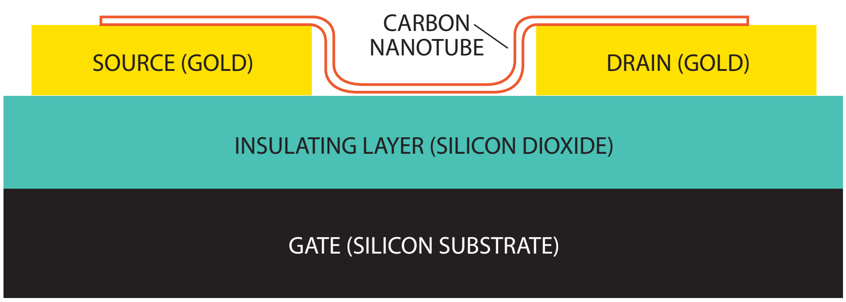
The other major arena for the small tubes is in materials. Nanotubes are about six times lighter and 10 times stronger than steel at the same diameter. But that's an awfully small diameter. "The strength of a nanotube is something that people have talked about quite a lot," says materials scientist Paul D. Calvert of the University of Arizona. "But in the end, the strength that counts is the strength of the thing you make out of it." Carbon fiber is already a proven winner in composite materials, and carbon nanotubes certainly have promise in the same market because of their exceptionally high length-to-diameter ratio, the vital figure in stress transmission. But there are miles to go to fulfill that potential. At a January meeting, Calvert recounts, "the nicest statement was from a group that demonstrated that carbon nanotubes do not degrade the properties of the epoxy resin. In other words, we can make something that's no worse than if we didn't put the tubes in at all."

One of the biggest boosters of future materials applications is the National Aeronautics and Space Administration, which hopes to find a place for nanotubes in everything from spacecraft to space suits. "But we have to figure out how to get the properties that are now on the nanoscopic scale up to something that we can use on a macroscale," says Bradley Files of the NASA Johnson Space Center of the nanotubes' low weight and high strength. "Every pound counts."

So does every dollar. "What concerns me is getting the cost down," Ebbesen says. Right now nanotubes run about 10 times the price of gold. With its relatively deep pockets, NASA may play a crucial role in all nanotube research. "We'd like to push the whole field," Files remarks. "We can't do all the work ourselves, and we see such breakthrough possibilities with the technology." Basic studies that uncover the secrets to growing specific types of tubes could also accelerate research and lower the cost.

Even if nanotubes fail to revolutionize the world directly, the research with them should still prove valuable, especially in tomorrow's advanced electronics. "They provide a great training ground for understanding electrical properties and behavior at very small dimensions," Avouris says. "Because one way or another—through nanotubes or through silicon or through other so-called molecular electronics—we're going to get there." —*Steve Mirsky*

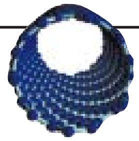




SEMICONDUCTING CARBON NANOTUBE, 1.5 nanometers in diameter (*left*), can be incorporated into a field-effect transistor, channeling current between the source and drain when an electrical field is set up by a voltage applied to the gate.

PHAEDON AVOURIS *IBM Thomas J. Watson Research Center* that may yield surprising new discoveries but will also require significantly more scientific research than will either nanocircuits or nanotube field-emission devices.

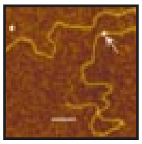
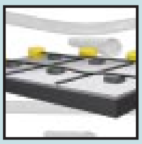
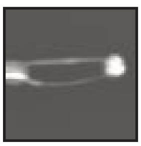
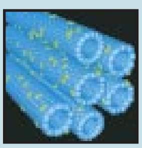
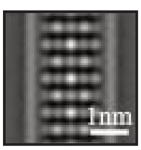
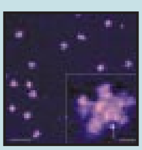
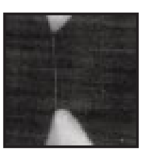
For example, researchers are currently debating exactly how electrons move along a nanotube. It appears that in defect-free nanotubes, electrons travel "ballistically"—that is, without any of the scattering that gives metal wires their resistance. When electrons can travel long distances without scattering, they maintain their quantum states, which is the key to observing effects such as the interference between electron waves. A lack of scattering may also help explain why nanotubes appear to preserve the "spin" state of electrons as they surf along. (Electron spin is a quantum property, not a rotation.) Some researchers are now trying to make use of



Other Uses for Nanotubes

Beyond Electronics

Feasibility Ratings
0 = Science Fiction
2 = Demonstrated
4 = Ready for Market

		THE IDEA	OBSTACLES	FEASIBILITY
	**Chemical and Genetic Probes** Tagged strand of DNA	A nanotube-tipped atomic force microscope can trace a strand of DNA and identify chemical markers that reveal which of several possible variants of a gene is present in the strand.	This is the only method yet invented for imaging the chemistry of a surface, but it is not yet used widely. So far it has been used only on relatively short pieces of DNA.	3
	**Mechanical Memory** Nonvolatile RAM	A screen of nanotubes laid on support blocks has been tested as a binary memory device, with voltages forcing some tubes to contact (the "on" state) and others to separate (the "off" state).	The switching speed of the device was not measured, but the speed limit for a mechanical memory is probably around one megahertz, which is much slower than conventional memory chips.	2
	**Nanotweezers** Pincers five microns long	Two nanotubes, attached to electrodes on a glass rod, can be opened and closed by changing voltage. Such tweezers have been used to pick up and move objects that are 500 nanometers in size.	Although the tweezers can pick up objects that are large compared with their width, nanotubes are so sticky that most objects can't be released. And there are simpler ways to move such tiny objects.	2
	**Supersensitive Sensors** Oxygen sticks to tubes	Semiconducting nanotubes change their electrical resistance dramatically when exposed to alkalis, halogens and other gases at room temperature, raising hopes for better chemical sensors.	Nanotubes are exquisitely sensitive to so many things (including oxygen and water) that they may not be able to distinguish one chemical or gas from another.	3
	**Hydrogen and Ion Storage** Atoms in hollow core	Nanotubes might store hydrogen in their hollow centers and release it gradually in efficient and inexpensive fuel cells. They can also hold lithium ions, which could lead to longer-lived batteries.	So far the best reports indicate 6.5 percent hydrogen uptake, which is not quite dense enough to make fuel cells economical. The work with lithium ions is still preliminary.	1
	**Sharper Scanning Microscope** Individual IgM antibodies	Attached to the tip of a scanning probe microscope, nanotubes can boost the instruments' lateral resolution by a factor of 10 or more, allowing clearer views of proteins and other large molecules.	Although commercially available, each tip is still made individually. The nanotube tips don't improve vertical resolution, but they do allow imaging deep pits in nanostructures that were previously hidden.	4
	**Superstrong Materials** Nanotube stress test	Embedded into a composite, nanotubes have enormous resilience and tensile strength and could be used to make cars that bounce in a wreck or buildings that sway rather than crack in an earthquake.	Nanotubes still cost 10 to 1,000 times more than the carbon fibers currently used in composites. And nanotubes are so smooth that they slip out of the matrix, allowing it to fracture easily.	0

Compiled by W. Wayt Gibbs, staff writer