Allotropes of Carbon

It’s all in the way you’re put together

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Allotropes of Carbon:
It's all in the way you're put together

Author: David Sederberg
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Grade Level: 8-12

LESSON OVERVIEW

Estimated Total Time of Lesson: 2 ½ to 3 hours

Lesson segment:	minutes
Leading questions and setting of format	5
Part 1 – models and study guide questions	40
Discussion	10
Part 2 – buckyballs and nanotubes	40
Discussion	15
Video, "Race to Catch a Buckyball"	50

Lesson Description

Topic: This lesson explores four common allotropes of carbon and builds on the concept that the geometric arrangement of atoms and the nature of the forces connecting them are just as important as the kind of atoms in determining the properties of the material. An emphasis is placed on carbon nanotubes and buckyballs, focal materials in nanoscience.

How the topic is contextualized: The discovery of the buckyball, soon followed by carbon nanotubes, turned carbon chemistry topsy-turvy. The lesson builds on the unique and revolutionary structural aspects of these newly discovered forms of carbon, within the context of topics relevant to existing curricula and standards: the atom as a fundamental unit of matter, bonding and hybridization, molecular geometry, and the particle nature of matter.

Importance of the topic: Buckyballs and nanotubes are already beginning to be exploited for their electronic properties, tensile strength and hollow caged structure; yet, there is still debate between possible benefits and risks to society and the environment. Uses of nanoscale structures like buckyballs and nanotubes will require socio-scientific consideration of any potential adverse impact they may have on the environment and health.

Description of what the students will do to investigate the topic: Learning will focus on the buckyball and the carbon nanotube and will model how, using shape and dimension, it is possible to correlate the structural elements of a material to the properties that it exhibits. Students will build and compare models of allotropes of carbon to construct an understanding of the relationship between structure and exhibited or predicted properties.

Learning Goals

Students will be able to:

- Characterize allotropes in general and provide the names for four allotropes of carbon.

Allotropes are variations in the forms of an element which differ in molecular composition or the way in which atoms form different packing arrangements in the solid state. The four allotropes of carbon are diamond, graphite, buckyball (C-60), and carbon nanotubes.

- Draw diagrams of the ways the carbon atoms are joined to show the geometric differences among buckyballs and the three different configurations of carbon nanotubes.
- Describe a process by which buckyballs and carbon nanotubes are synthesized in the laboratory and explain how this is an example of bottom-up fabrication.

  Buckyballs can be grown from the deposition of gaseous carbon atoms formed by laser ablation or electric discharge across graphite rods. Nanotubes are grown by a similar process, but the growth is commonly nucleated by a catalyst on a substrate. In all cases, these structures spontaneously assemble from single atoms or groups of atoms into larger structures, all of which are examples of bottom-up fabrication.

- Compare the three structural features among varieties carbon nanotubes and predict possible technological applications for which structures such as these might be useful.

  The carbon atoms in a nanotube grow in three general types of arrangements, armchair, zig zag, and chiral. These terms refer to the way in which the atoms are connected around the circumference of the tube and have an effect on the electrical and mechanical characteristics of the tube. Carbon nanotubes have also been shown to be as much as 200 times stronger than steel at a fraction of the mass of material.

Big Ideas in Nanoscale Science and Engineering

- *Size and Geometry*: The concepts of size, scale and shape contribute to the cognitive framework for making sense in science, both to locate realm of study (e.g., macro, micro, nano, atomic) and the tools making it accessible, as well as to contextualize factors for understanding and predicting behavior (Stevens, et al., 2009).

  Buckyballs and nanotubes, with dimensions in the 1 to 10 nm range exhibit the high proportionality (aspect ratio) between dimensions characteristic of nanoscale materials. Carbon nanotubes, for example can have aspect ratios upwards of 10 000 000 to 1, meaning that they can be 10 000 000 times longer than their diameter!

- *Models and Simulations*: Modeling is a critical tool for scientists, combining evidence with creativity providing both explanatory and predictive powers. The extremely small size and complexity of nanoscale targets make models and simulations essential for the study and interpretation of nanoscale phenomena (Stevens, et al., 2009).

  Creating a model of the buckyball made it possible for scientists to predict properties of the molecule prior to actually isolating it in the laboratory. The unique hollow caged structure of buckyballs and carbon nanotubes was only revealed through the creative construction and manipulation of models.

- *Science, Technology and Society*: Nanoscience and engineering provide a platform for students to witness “science in the making” in real time and to become of the technological opportunities. Yet, as nanoscale technologies and materials continue to emerge, it is important to recognize potential adverse effects to life and the environment from materials still to be fully investigated.

While nanoscale structures such as buckyballs and nanotubes offer great potential for commercial application in current, there is no consensus as to the potential adverse effects of their accumulating in organisms, the food chain or the environment. Could potential risks of these unnatural materials outweigh possible benefits?

Standards

Indiana State Standards (Indiana Department of Education, 2009)

Grade 8: 8.1.1; 8.1.8; 8.3.10; 8.3.18

Grades 9-12

Chemistry: C.1.26, C.1.28, C.1.35

Integrated Chemistry / Physics: CP 1.11

LESSON PREPARATION

Background for Teachers

The goal of this lesson is to introduce students to the realm of nanoscience and nanoscale materials in the context of carbon allotropes. Inquiry will focus on the structural characteristics of two of the most intriguing players in nanoscience, the buckyball and the carbon nanotube.

Do not define the term allotrope for students prior to or during the lesson. The final point of the lesson will be for students to synthesize their own definition of what allotropes are, based on evidence and interpretation. Likewise, it is not necessary to identify the models used as diamond, graphite, nanotube and buckyball in advance. Those terms will emerge in the lesson.

The lesson relates to the role that models play in science; how they are used, why they are used, what their benefits are, as well as their limitations. In the case of the buckyball, scientists had *evidence* that the molecule existed, but it was only through the creative use of models that they gained insight on where to look for further data. The teacher should,

- Have a familiarity with the concept of allotropy and elements other than carbon, which commonly form allotropes; elemental oxygen (O_2) and ozone (O_3) are examples. If appropriate, the concept of hybridization will be beneficial in explaining the geometries of bonds around individual atoms (see *allotropy* under **SUPPLEMENTAL MATERIALS**).
- Be able to relate the synthesis of fullerenes to the concept of bottom-up fabrication.

The video “Race to Catch a Buckyball” documents the serendipitous discovery of the buckyball and the creativity that often accompanies the generation of scientific knowledge. The story provides an excellent opportunity to help students realize that knowledge is socially constructed, negotiated, and forever changing, not a body of facts, which, once discovered, remain true. The video documents the isolation, fabrication and characterization of the buckyball, providing an epistemological foundation for scientific breakthrough.

See **SUPPLEMENTAL MATERIALS** for more information on these topics.

Student Prior Knowledge Expectations

Students are expected to have knowledge of atoms as the building blocks of matter and a basic understanding of the particle nature of matter. A familiarity with relative scale, to locate nanotubes and buckyballs in the regime of the nanoscale is suggested.

Potential Student Alternative Ideas

Several common pre-scientific or alternative ideas that students often exhibit include:

- *Nanotubes are made by rolling up sheets of atoms.*

  People (even scientists) often refer to the nanotube as a rolled up sheets of graphene. Likewise, since the nanotube model in this lesson is constructed by rolling a transparency sheet into a tubular structure, students often come away believing that this models how the tubes are made commercially. ***Carbon nanotubes are not made by rolling up graphene sheets!*** Reinforce to students that this is merely a *model*, used in order to visualize and classify the various types of tube conformations.

- *Nanotubes and buckyballs are made by selectively positioning atoms together.*

  While, with the aid of atomic force microscopy, it is possible to transfer one atom at a time from one position to another, this would be too laborious a process to be practical for any synthesis of nanoscale materials. Buckyballs and nanotubes are "grown," often using a catalyst, by the natural forces of atoms bonding together.

Potential Student Difficulties

- Students may need help in getting started cutting out the paper template to make the model of the buckyball. They sometimes fail to understand what gets cut away and what remains of the paper.
- It is also difficult for some students to know where and how to start gluing the paper buckyball model together. The gluing positions are sequentially numbered to help students begin.

Materials (per class of 24 students, working in pairs)

Item	Number/Amount
Commercial model kit(s) (graphite, diamond, buckyball)[1]	4-5 of each
Paper model buckyball templates[2]	24 (1 per student)
Nanotube transparencies (hexagonal graph paper)[3]	36 (3 per group)
Glue pen [4]	12 (1 per group)
Scissors	24 (1 per student)
Masking tape	1 roll
Sample of graphite rock[5] (optional)	6
Glass diamond-cut paperweight[6] (optional)	6
NOVA Race to Catch a Buckyball[7]	1

[1]Available from **Flinn Scientific** (www.flinnsci.com) and **Science Kit** (www.sciencekit.com).
[2]Master provided with lesson (from www.nasaexplores.com). Print on 65# or 70# card stock.
[3]These can be re-used with each class. The master is provided in PDF format with this lesson.

[4]Use **Avery** brand Glue Pen (#65781, Avery Permanent Bond Disappearing Color Glue Pen). Other brands are not as strong and are not dry on contact. The only office superstore with these in stock is **Staples**.
[5]**Science Kit** (www.sciencekit.com)
[6]Available from Hobby Lobby or on-line houses for approximately three dollars.
[7]This **NOVA** episode aired in 1996; it is of print and no longer available for purchase. Public and school libraries are potential sources.

Pre-Class Preparation

Getting the Materials Ready

- Print the buckyball model templates. The paper model is printed from the PDF template provided with the lesson on a single sheet of paper, 8 ½ x 14. Students should make their own individual models, allowing a "take-home" artifact of the learning experience. The model can be printed on regular copy paper, but using 65# or 70# paper stock will be more durable and easier to construct. Using different colors may increase student engagement.
- Print the nanotube models using overhead transparency film. In order to compare the structure among the three configurations of the carbon nanotube, each team will be provided three identical transparency templates. The transparencies may be re-used for multiple classes. These models can be printed from the PDF template supplied with this lesson.

DOING THE LESSON

Opening

- Explain to students that the purpose of this lesson is to introduce them to two important materials in nanoscience, based on the element carbon.
- Begin by eliciting students' existing knowledge by asking or having them write down what they know about the element carbon:
    - *What is carbon? Have you seen carbon? What did it look like?*
    - *Are there any things or types of materials that are made up entirely of carbon?*
    - *How are these materials different; how are they the same?*
- We begin the lesson with some samples of carbon materials, some small pieces of graphite and charcoal, and for fun, a glass "diamond" from the hobby store. Students can examine these materials first hand and predict what it is about these materials that make them so different, given that they are theoretically all pure carbon.
- The procedure for the investigation outlined below is also provided in the **Student Study Guide** for this lesson.

Concept Development

Student Study Guide - Part 1: - Models of Carbon

1. On the student activity guide, students will be asked to examine and investigate models of four allotropes of carbon (diamond, graphite, nanotube and buckyball) and to draw a representation of the structural features of each. The models are only identified by number. As a part of the investigation, students will be asked to match name with structure, once features of the allotropes have been discussed.

   Note: We have purposefully avoided use of the terms ***atom*** and ***bond***. The reason for this is to elicit students' perceptions based on their prior experience and existing knowledge and to let these terms emerge as meaningful concepts to describe the materials.

2. Students will be asked to complete a table listing similarities and differences among these four types of carbon. At this point in the investigation, pause to discuss students' findings by eliciting students' responses and compiling a tentative class list. Through this discussion, terms like atom and bond will emerge as meaningful tools for describing these structures. Other comparisons will include:

   - ✓ Repeating patterns of hexagons and pentagons
   - ✓ Hexagonal rings that are flat versus puckered
   - ✓ Structures that are "packed" or hollow
   - ✓ Number of atoms attached to other atoms

3. Have students answer questions in Part 1 of the Student Packet.

   Question 1 at the end of ***Part 1*** asks students to synthesize their own definition of the term allotropes, based on their conceptions generated as a result of the inquiry. These can be written on a separate sheet and collected, or read aloud and key features compiled as a class list. Through class discussion, the teacher can guide students to an understanding of the nature of the term.

   It would also be appropriate to provide examples or discussion of other common and familiar elements that form allotropes, so that students realize that allotropy is not unique to carbon. See *Allotropy*, under **SUPPLEMENTAL MATERIALS** at the end of this packet.

Before moving on, make sure students understand how to represent atoms and bonds, and can describe the relationship among them. They should recognize that in the diamond structure, each carbon is bonded to four other carbon atoms. Reinforce at every opportunity the utility versus the limitations of using models such as these and that while models never really correspond to the real thing, they are useful to aid in understanding, to provide a power of explanation of evidence, for conveying information to others or for making predictions.

It is important that the structure of graphite is discussed in terms of the type of bonding arrangement (three bonds per carbon atom) and that all bonds are in the same plane. Between planes there are no chemical bonds, only van der Waals forces, weak interactive forces. The planar sheets a single atom thick making up the structure are referred to as graphene. Actually, the reason that the graphene sheets slide past one another is due to the presence of water vapor trapped in the spaces between them. Models of graphite may be especially limited in that they portray the graphene sheets as fixed in position. This will be addressed further in the discussion following the questions below.

Diamond is unique among the allotropes of carbon in that it is the only one to have tetrahedral sp^3 hybridized atoms. The bonds are not all in the same plane, whereas with graphite (with sp^2 hybridization) they are in the same plane. The effect of these variations results in the number of atoms attached to others, and the overall geometric arrangement of atoms in the structure, both of which have a direct impact on properties.

Student Study Guide - Part 2: Buckyballs and Nanotubes

This part of the lesson will direct students' investigations to two key materials pertinent to nanoscience, the buckyball and carbon nanotube.

1. Students will construct the buckyball model from the template provided. Students will draw a representation of their model on the report sheet or in their laboratory notebook.
2. Discuss the key structural aspects of the buckyball. Students often fail to realize that it is a hollow structure which, unlike any material except those at the nanoscale, has *all of the atoms on the surface*. Potential uses of the buckyball will likely depend on these unique features, such as being able to transport single molecules into living cells, either as sensory devices for diagnosis or as a means of delivering treatment at a cellular level.

Useful in eliciting the level of students' conceptual understanding, and highlighting some of the key aspects of the structural nature of the buckyball, the student study guide includes the following questions:

(1) Knowing that the geometric arrangement of atoms in a buckyball yields 12 pentagons and that all of the atoms in the structure lie at the vertices of a pentagon, describe a line of reasoning to determine the total number of carbon atoms in a buckyball.

Students might take a stepwise approach to this question, along the lines of:

- ✓ *There are 12 pentagons in the structure*
- ✓ *Each pentagon includes 5 atoms*
- ✓ *All of the atoms are in pentagons*
- ✓ *12 pentagons times 5 atoms per pentagon equals 60 atoms*

Alternately a student could merely write, *5 x 12 = 60 as a line of reasoning*.

What would the chemical formula be for a buckyball? C_{60}

(2) If you could examine the *inside* of a buckyball, what would do think you would find?

Nothing, inside the buckyball is empty space.

Alternately a student might consider the appearance of the inside of the buckyball from an inside the ball perspective,

The inside of the of the ball looks exactly like the outside.

In either case, the main feature of the buckyball is that it is hollow, as will also be seen in investigating the nanotube. These caged structures are unique among molecules and are one of the reasons that these materials pose some interesting application possibilities.

(3) Scientists think that buckyballs could someday be used to transport other molecules into living cells for diagnosis and treatment of disease. What do you think would keep the molecules from "leaking out?"

Chemical bonds consist of shared electrons, so where a bond exists there are electron clouds between atoms. The electrical nature of these electrons clouds poses a charge barrier that makes it difficult for other chemical species (also bounded with electron clouds) to penetrate.

3. Similar to the previous activity, students will draw models of carbon nanotubes, based on their interpretations of the structures and answer the questions in the study guide. To begin the section for nanotubes, the teacher will do the following:
   - Provide each group with three overhead transparencies of the hexagonal grid, representing a two dimensional graphene sheet.
   - Ask students to find three different ways in which to curl the sheets into cylinders, making three different arrangements of atoms. The models can be taped together using a small piece of masking tape.

The following questions are included in the student study guide:

(1) What do the lines in your transparent models represent? Chemical bonds

(2) Where are the atoms in these models?

At the vertices of the hexagons; there is a single carbon atom at the vertex of each pentagon.

(3) What do you think would be inside a real nanotube? Empty space; nothing

(4) Examine your nanotube models.

(a) Describe how you could distinguish each type of nanotube from the others.

The nanotubes vary in the way the atoms are arranged around the circumference. Hexagons are oriented differently; vertices pointing parallel with the length of the tube, or pointing in line with the circumference. Or, the atoms are not in line in any way straight across a dimension of the tube, but form a spiral in a helical pattern.

(b) Give each of the models a name that you could use to distinguish one from another.

4. Discuss the structural characteristics exhibited by the models; how the three tubes are different, what is unique about the arrangement of atoms, how one can be visually described relative to the others; how other arrangements may be possible. Alternatives do exist in that the degree of offset in matching the two sides together can vary. This provides variation in the degree to which the atoms "spiral" around the circumference of the tube, a consequence referred to as *chirality*. Discuss with students how they perceive models in light of their own conception of the structure of matter; where are the 'atoms'?; what is between the atoms?; and what is inside of the structure? (See *modeling* under **Wrap-up**).
5. Modeling the structure of nanotubes in this way often gives students the impression that rolling up single atom thick sheets of graphite is how carbon nanotubes are fabricated.

Discuss how tubes are grown from a catalyst substrate and "harvested" and that by varying the catalyst and the conditions of the reaction growth can favor one type of configuration more than another. We do not yet have the capacity to make one variety of carbon nanotube selectively and in large quantity.

6. When students are ready they can draw representations of the group's three "buckytube" models on their report sheet or in their laboratory notebook and answer the corresponding questions from the student packet. The questions and their answers are shown below:

(1) Think about the models of the allotropes of carbon and how you imagine the real molecules might exist.

a. Explain in what ways you think the models are *like* the real thing.

Possible answers might include:

In the case of the buckyball, the models show the correct number of atoms for the molecule.
The models indicate the number of bonds to each carbon; the number of neighboring atoms to another atom.

b. What do you think that the models *do not* tell you about real materials the models represent?

They do not show the relative scale of the size and spacing of the atoms and bonds.
They do not convey the vibrational nature of atoms; that atoms are in constant motion and that that motion increases with temperature.

(2) Buckyballs and carbon nanotubes are still fairly new to scientists in the sense that some of their properties, as well as their potential hazards, are not known.

a. Some people believe that when new materials, such as buckyballs and nanotubes, are advanced through technology, we should utilize them to their fullest potential for the maximum benefit to all. What is your opinion?

b. Why might some people have fears regarding new materials like these?

(3) Despite their size, nanotubes have been shown to be as much as 200 times stronger than steel. Their electrical conductivity also varies with the three configurations, from conductor, semi-conductor, to non-conductor. Based on these properties, what do you think might be some possible uses for carbon nanotubes?

(4) What do you think is the single most significant feature of buckyballs and nanotubes, compared to the other forms of carbon materials?

The most significant feature of nanotubes and buckyballs is that they are hollow. In the case of the buckyball alone, it is the only allotrope that has a definite formula; the other allotropes vary in number of atoms, depending on the size of the piece.

(5) If you were to select one significant feature, more than any other, that makes the buckyball unique from the other allotropes, what would that one feature be?

The buckyball is the only one of the carbon materials that is a molecule; it has a specific formula. There is no one formula for diamond, graphite or nanotubes, they can be any size.

7. While the diamond and graphite bond geometries are predictable based on structure, the angles between bonds in the buckyball and nanotube vary due to the bending of the bonds to make an enclosed structure.

Allotrope	Hybridization of carbon atoms	Geometry around each atom	Bond angle around atom
Diamond	sp^3	Tetrahedral	109.5
Graphite	sp^2	Trigonal planar	120
Buckyball	sp^2	--	--
Nanotube	sp^2	--	--

It is not important that students memorize the data in this table. What is important is that they realize that carbon, like most other semimetals and many non-metals, can form bonds in a number of different geometries and that these shapes have an influence on the properties exhibited by these materials. In the case of buckyballs and nanotubes, the behavior of these structures is even more unique due to their being closed cages.

8. Talk about, or assign readings from the literature or internet if desired, the varied current uses of the allotropes of carbon which rely on a specific property. Uses for buckyballs and nanotubes are still unfolding, but are likely to involve uses at the molecular and cellular levels rather than using these materials in a bulk form.

Video- Race to Catch a Buckyball

1. Discussing briefly with students what a mass spectrum is prior to watching the video will be beneficial to their understanding the examples shown, even if they do not specifically know how to interpret them. Spectra from the literature are provided (see *The mass spectrum* under **SUPPLEMENTARY MATERIALS**.) These figures are from the paper (Cox, et al., 1988) actually referred to in the video. Having several copies of the paper for students to see in advance will enable them to actually see a real history-making journal research paper!
2. Once students have completed their models and answered the report questions, move on to the NOVA video, *Race to Catch a Buckyball*. The video should need little introduction. The teacher might show students, however, what a mass spectrum looks like, what it represents, how it is generated and what the individual peaks represent.
3. Discuss with students the construction of scientific knowledge that emerges through the abductive creativity from experimental evidence. Students often believe science to be little more than amassed facts, know with certainty and the generation of knowledge by scientists in the video well documents the tentative and socially negotiated nature of knowledge.

Wrap-up

Structure and function

Discuss the similarities and differences in the types of forces interacting (bonds) between the atoms among the four allotropes, and how these differences account for the varied properties exhibited. Include angles and geometries around the atoms and hybridization in your discussion. Points for discussion might include:

- The most distinguishing characteristic separating the buckyball and nanotube from the other allotropes in their hollow cage structure. Uniquely, all atoms in these molecules are surface atoms. Unlike all of the other allotropes, the buckyball, and its variations (e.g., C_{60}, C_{70}) are the only members of the carbon allotropes currently known that are stable molecules; they have a definite formula.
- Diamond is the hardest substance known because of the bonding pattern of its carbon atoms. Each atom has four covalent bonds, which join it to four neighboring atoms. The bonds are oriented at angles of 109° to each other, as though they were pointing toward the corners of a tetrahedron (sp^3-hybridized geometry). The hardness of diamond is attributed to the three dimensional covalent network bonding among the atoms.
- Graphite, the black material in lead pencils, has little physical strength because its atoms are bonded to each other in only two dimensions (sp^2-hybridized geometry). The resulting flat sheets readily slide over each other, a consequence of the *two-dimensional* nature of the carbon bonds within the overlaying ‘sheets’. The rings of graphite are aromatic and, with a structure analogous to the benzene ring, have de-localized pi electrons which can move freely throughout the graphite sheet. This explains why graphite is the only nonmetal found in nature that conducts electricity.
- The specific hybridization of carbon 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, C_{60}, or carbon nanotubes, depending on the conditions under which the synthesis is performed. While in graphite, the sheets of atoms are perfectly planar, in the structures of the buckyball and nanotube, sp^2 hybridized carbons form rings that are attached to each other in a puckered arrangement. This is evident from looking at the models constructed.

Modeling

In building paper models of molecules, such as the buckyball, the corners, or vertices, represent the locations of atoms in the molecule. Each vertex represents an atom. A Buckyball has 60 vertices, 60 carbon atoms, and no interior atoms. That is why a Buckyball is called C_{60}, or carbon-60. Likewise, with the transparent nanotube model, each “corner” of every hexagon represents an atom. Three-dimensional shapes that are constructed of patterns of the same shape, such as cubes, are called regular polyhedra. If students examine a soccer ball, they will find that is not a regular polyhedron because it contains both hexagons and pentagons. It has the same structure as a Buckyball.

Students are purposefully not told the name or the atomic arrangement of the three different nanotube configurations. This will be determined in class discussion, after students have created their own versions of names for the carbon structures created. Probe students’ perception and interpretation of the models and see how they might distinguish among them. They are likely to even suggest names that might be more intuitive than the scientifically accepted ones, but again, that process illustrates the manner in which knowledge and terminology is socially constructed. Ultimately, the name of the three types of tubes should be provided and discussed.

One model is called the zig-zag configuration.

A second model is the chiral configuration.

The third model is referred to as the armchair configuration.

Zig-zag

Chiral

Armchair

Images from http://cobweb.ecn.purdue.edu/~mdasilva/Structure.shtml

You may elect to have students count the vertices and the number of hexagons and pentagons after they finish the paper buckyball models. As an alternative, prior to cutting out the patterns, they can identify the positions of the atoms beforehand by drawing a dot with a marker at each vertex. Then, when the buckyball is assembled, the dots will clearly show the geometric arrangement of atoms in the structure. This can be done to reinforce the interpretation of the model in terms of the difference between the atoms and the bonds between the atoms.

If bonding is an appropriate topic for the class, students can draw a line along the crease between all pairs of hexagons after the model is completed. These lines represent the double bonds shared by adjacent carbon atoms. Each hexagon should end up with single bonds and double bonds alternating around its perimeter, for a total of three single and three double bonds.

How long a hair? – A mathematical note

CNT have been produced with aspect ratios in the range of 30 000 000: 1. Given that a typical single walled carbon nanotube has a diameter in the range of 1 nm, it might be interesting to calculate the length of a carbon nanotube, scaled up to the diameter of a human hair. In other words, how long would the nanotube be if it were enlarged to the same diameter as a hair, approximating the diameter of a hair to be about 0.50 µm? Your students will be astounded!

Adaptations

The research literature

If it is appropriate to the grade level of student, it may be enlightening to provide them with copies of the original journal articles announcing the discovery of the buckyball (Cox, et. al., 1988; Kratschmer, et. al., 1990; and Kroto, et. al., 1985). All if these papers are cited in the references.

A connection to geometry

A main challenge faced by the scientists in the video is to determine the structure of a type of carbon molecule that had never been known previously. To provide students insight, you may want to have them try, or demonstrate, some simple tessellation activities. Tessellations are shapes which, when fitted together, will cover a flat surface with no gaps. Squares and rectangles are particularly easy to tessellate; pentagons, one of the shapes confronting buckyball researchers will not tessellate. Tessellations can be found in the pattern of tiles that cover bathroom walls and the brickwork patterns in building walls and pathways. Tessellations are commonly found in nature, from snake skin to the outside of pineapples or armadillo shells, to natural rock formations and lava flows. Honeycombs, spider webs and the pattern of corn on the cob are further examples, as well as the geometric works of the Dutch artist, M. C. Escher.

One of the challenges facing researchers in the elucidation of the structure of the buckyball was finding a geometric arrangement around which atoms would "fit" within the normal parameters of their bonding patterns and angles (NOVA, 1995).

RESOURCES

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SUPPLEMENTAL MATERIALS

Summary of Lesson

When an element can exist in more than one form, either as a result of differences in molecular composition or from different packing arrangements of atoms in the solid state, these forms are called allotropes. Allotropes often have vastly different physical and chemical properties, even though they are composed of identical atoms of the same element.

Through the building and manipulation of models, this lesson is intended to help students understand the relationship between the structure and spatial arrangement of atoms within a material and the characteristic properties that the material exhibits. This relationship is pronounced at the nanoscale where the the proportionality between dimensions, like surface area to volume or length to diameter, is extreme and the resulting structure related properties are profound.

This lesson, accompanied by the video "Race to Catch a Buckyball" will also provide students the opportunity to delve into the relevance of scientific research and the role of serendipitous discovery in the building of scientific knowledge.

Supplemental files

PDF; Nanotube Transparency Template (8 ½ x 11 inches).
PDF; Paper Buckyball Model (8 ½ x 14 inches).

Standards

Indiana State Standards (Indiana Department of Education, 2009)

Grade 8

- 8.1.1 Recognize that and describe how scientific knowledge is subject to modification as new information challenges prevailing theories and as a new theory leads to looking at old observations in a new way.
- 8.1.8 Explain that humans help shape the future by generating knowledge, developing new technologies, and communicating ideas to others.
- 8.3.10 Explain that increased temperature means that atoms have a greater average energy of motion and that most gases expand when heated.
- 8.3.18 Investigate and explain that electric currents and magnets can exert force on each other.

High School

Chemistry

- C.1.26 Describe physical changes and properties of matter through sketches and descriptions of the involved materials.
- C.1.28 Explain that chemical bonds between atoms in molecules, such as H_2, CH_4, NH_3, C_2H_4, N_2, Cl_2, and many large biological molecules are covalent.
- C.1.35 Infer and explain physical properties of substances, such as melting points, boiling points and solubility, based on the strength of molecular attractions.

Integrated Chemistry / Physics

- CP.1.11 Understand and give examples to show that an enormous variety of biological, chemical, and physical phenomena can be explained by changes in the arrangement and motion of atoms and molecules.

Subject Matter Knowledge for Teacher

Carbon in a nutshell

The element carbon is the backbone of life on our planet. Carbon, like most other elements heavier than helium, was synthesized in the stars. On our own planet has been cycled and recycled from earthen minerals into the air, through animals and plants and back again countless times. Carbon has been a familiar and useful material since prehistory, in the form of charcoal and soot, although it was not until late in the eighteenth century that carbon actually came to be recognized as an element (Greenwood & Earnshaw, 1984).

The name carbon was actually coined by Antoine Lavoisier (Fr. carbone) from the Latin *carbo* meaning charcoal. Swedish chemist Carl Wilhelm Scheele showed in 1779 that graphite, a familiar sooty material, consisted only of pure carbon (Greenwood & Earnshaw, 1984). That a diamond was composed only of carbon as well was demonstrated just a few years later by both Antoine Lavoisier and Humphry Davy, each of whom independently performed the costly experiment of burning diamond in excess oxygen, identifying as the only product, carbon dioxide. Thus, by the end of the 1700s, diamond and graphite were proven to be composed of atoms of the same element – carbon, except that they existed in physically different forms (Zaugg, 1990).

The word diamond comes from a blend of the ancient Greek words *diaphanes*, "transparent" and *adamas*, "invincible," referring to its extreme hardness. The name "graphite," proposed in 1789 from the Greek, *graphein*, to write, illustrates one of the uses for this form of carbon (Greenwood & Earnshaw, 1984).

Diamond is the standard for hardness against which the hardness of other materials is measured. Pure diamond is colorless and transparent. It has the highest melting point of any known substance. It is the hardest of any naturally occurring solid and it was the first material to have its crystalline structure determined by x-ray diffraction (Gale, 2005).

In contrast to diamond, graphite is blackish, waxy, soft and slippery feeling, but is more thermodynamically stable than diamond. Graphite is composed of carbon atoms, each bonded to three other carbon atoms, arranged in a repeating hexagonal pattern in flat two dimensional sheets. These sheets, held together by only weak attractive forces, and 'lubricated' between layers with molecules of water or air, stack together to make the solid. These two materials, diamond and graphite, vastly differ in both their appearance and in their properties, yet, despite their obvious differences, both are pure carbon; both are composed of identical atoms.

Allotropy

Like carbon, a number of elements (for example, B, P, Sn, Pb and S), exist in different forms, different physical arrangements of the atoms, each possible arrangement contributing to contrasting and unique properties. When an element can exist in more than one form, either as a result of differences in molecular composition or from different packing arrangements of atoms in the solid state, these forms are called *allotropes*. Allotropes often have vastly different physical and chemical properties, even though they are composed of atoms of the same element.

In the two hundred years following the work of Lavoisier and Davy and until recently, the number of allotropic forms in which carbon was known to exist was only two - diamond and graphite. Events in 1985, however, brought a paradigm shift to the field of carbon chemistry with an epic history-making discovery. Two graduate students, working in the laboratory of Richard Smalley at Rice University, discovered the existence of an entirely new form of carbon, in fact a whole family of stable carbon molecules, the most abundant species of which was a molecule of sixty atoms, C_{60}. A slightly larger molecule C_{70}, also appeared as a stable species in the mix. The carbon atoms in these molecules had assembled from carbon vapor into solid molecular units – stable molecules with a specific number of carbon atoms, resistant to further growth or modification, (Kroto, et. al., 1985).

The research team at Rice worked tenaciously with paper models, jelly beans and toothpicks, geometric solids, and creativity, fitting experimental evidence with the known chemical behavior of carbon, attempting to figure out how the atoms in these molecules were connected together. Throughout months of frustration and uncertainly, the structure of the buckyball eluded them.

Ultimately, the only structure which could offer a reasonable explanation for this behavior, and still provide each carbon atom with its correct compliment of electrons, was a spherical one. These spherical structures were eventually shown to be composed of a repeating geometric arrangement of hexagonal carbon rings, resembling a geodesic dome. The surprising anomaly of these structures, however, compared to the previously known carbon allotropes, was that they contained a *specific number of carbon atoms* – they were *molecular* carbon. These new carbon molecules appeared to form from the carbon vapor surrounding them, programmed to some predetermined size and exact number of atoms. Richard Smalley, Robert Curl, and Harold Kroto were awarded the Nobel Prize for their work in 1996.

Paying homage to Richard Buckminster Fuller, an architect famous for his work designing geodesic architectural domes, Smalley and Kroto named this family of molecules *Buckminsterfullerenes.* They are more commonly referred to as fullerenes, or, more affectionately, just "buckyballs." With this discovery, a new and revolutionary third allotrope of carbon had now been added to the two (graphite and diamond) already known. Although initially found as laboratory anomalies, fullerenes have since been shown to occur in nature, on the earth as well as in space. While a number of varieties of buckyballs have now been shown to exist, C_{60} and C_{70} are generally the most abundant and readily isolated fullerenes (Kroto et al., 1985).

In 1991 another variety of fullerenes were discovered, with properties similar to the buckyball, but in a tubular, rather than spherical shape. The diameters of these "**buckytubes**" fall in the 1 to 10 nanometer range and as such were referred to as **nanotubes**, or carbon nanotubes (CNTs). Although the mechanism of their formation has not been fully characterized, they are typically grown with the aid of a catalyst on a substrate. While CNTs resemble the look of a "rolled up" section of a graphite sheet, their synthesis is bottom up. The variety of ways in which the carbon atoms align to form these tubes can create a variety of arrangements, all with different mechanical strengths and physical properties.

The mass spectrum – using the evidence

Evidence that there may be a new and unknown form of carbon arose from speculation from the UV and IR spectra from stars. Matching evidence from the laboratory to what scientists had available gave support to the theory that there may be a new form of carbon, in a molecular shape never before seen. Soon after discovering that they had created a new form of carbon in the laboratory, scientists began trying to create a model of this molecule.

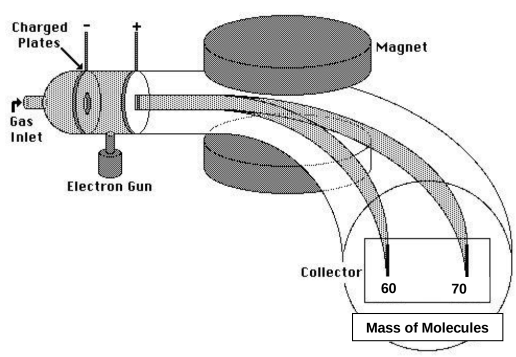
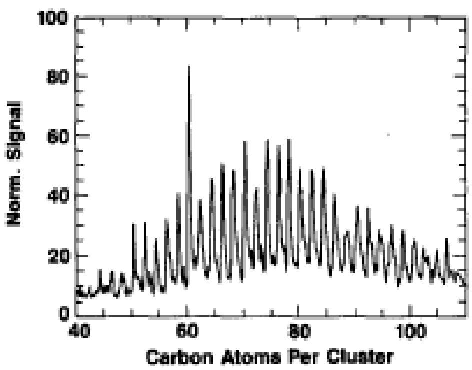
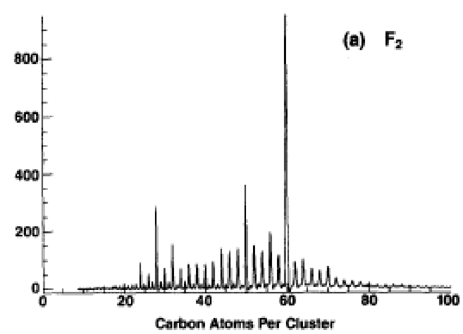


Image adapted from
www.hcc.mnscu.edu/chem/abomb/Mass_Spec_of_U.jpg

Even when scientists were successful in creating the "buckyball," they still had not been able to isolate a pure sample or see a single molecule of Carbon 60. This exemplifies one role of the model in science, providing scientists a direction in which to look for new evidence. Ask the students to reflect on this process of developing and testing a theory from evidence and observation. What evidence was available to scientists that helped them create their model? Did all scientists view that evidence equally? How did they evaluate and revise their ideas? How was the knowledge of science changing? What evidence helped then to confirm their theory? What evidence required the changing of their theory?

One of the crucial pieces of evidence in the elucidation of the structure of the buckyball was the mass spectrum. A mass spectrum of a molecule is obtained by ionizing molecules or fragments of molecules which are accelerated through a magnetic field which deflects the fragments differentially based otn he mass of the fragment. The most common molecular entity consistently contained 60 atoms, suggesting this to be a stable structure. Provided evidence of the stability of a 60 carbon molecule, scientists then set out to determin its structure. Shown below are two mass spectra taken from this experimental research.





(Images fromCox, Reichmann, & Kaldor, 1988)

Allotropes of Carbon

Student Study Guide Name ___________________________________

In this lesson you will examine some materials that are composed only of the element carbon. You will be provided models, labeled for identification, as model one, two, three and four, representing each of the materials.

Part 1 – Models of Carbon

Examine each of the models and diagram the structure in its respective box below. Draw enough of the structure to show any repeating patterns and shapes.

Next to each of your drawings, describe in a way that you could use to explain to someone else, the structural characteristics and key features of the material.

Model One

Description

Model Two

Description

Model Three

Description

Model Four

Description

Using the models and the drawings you have created as a guide, list as many aspects of these materials as you can that are similar or different among them.

Similarities	Differences

Discussion

After a discussion of similarities and differences among these forms of carbon, what do you know now that you didn't know before?

Questions

1. The different carbon materials that you have been examining, all of which are composed only of carbon, are referred to as "allotropes." Based on the evidence that you have gathered over the course of investigating these models, how would you define the term allotrope?

2. The models you have been examining actually correspond to four allotropes of carbon, which are listed below. Write the number of the model that you think corresponds to the given allotrope in the blank next to the name.

	Model
Graphite	______
Nanotube	______
Diamond	______
Buckyball	______

In **Part 1** of this lesson you examined four common allotropes of carbon. Two of the members of this family, the buckyball and the carbon nanotube, are key players in nanoscience because of their unique structure, and potential. In **Part 2**, you will take a closer look at the structures of these materials.

Part 2 – Buckyballs and Nanotubes

1. Cut around the perimeter of the buckyball template
2. Cut along each dotted line to the darkened shape.
3. Cut out the shaded areas.
4. Beginning with the first numbered space, apply glue using a glue stick, on the side where the number is printed. Slide this ring under the adjoining ring, making a *five-sided hole surrounded by hexagons*.
5. Continue gluing the numbered shapes, making pentagon holes as you go, until the model in completed.
6. Draw a picture of your buckyball model in the box to the right. You do not have to draw the entire structure, but draw how it looks from one side of the sphere.

Questions:

1. Knowing that the geometric arrangement of atoms in a buckyball yields 12 pentagons and that all of the atoms in the structure lie at the vertices of a pentagon, describe a line of reasoning to determine the total number of carbon atoms in a buckyball.

   What do you think the chemical formula would be for a buckyball?

2. If you could examine the *inside* of a buckyball, what would do think you would find?

3. Scientists think that buckyballs could someday be used to transport other molecules into living cells for diagnosis and treatment of disease. What do you think would keep the molecules from “leaking out?”

4. What question would you want to ask so far about carbon nanotubes or buckyballs?

Comparing carbon nanotubes

Use the transparencies provided to you to make three different models of carbon nanotubes. Draw a sketch of each model to show the arrangement of the carbon atoms for each of three models. You do not have to draw the entire tube; just draw it from the perspective of standing it on end and looking at it from the front side.

model 1	*model 2*	*model 3*

Questions:

1. What do the *lines* in your transparent models represent?

2. Where are the *atoms* in your drawings?

3. What do you think would be *inside* a real nanotube?

4. Examine your nanotube models.
    a. Describe how you could distinguish each type of nanotube from the others.

    b. Give each of the models a name that you could use to distinguish one from another.

    Tube 1 Tube 2 Tube 3

Summary Questions:

1. Think about the models of the allotropes of carbon and how you imagine the real molecules might exist.
    a. Explain in what ways you think the models are *like* the real thing.

    b. What do you think the models do *not* tell you about the things that the models represent?

2. Buckyballs and carbon nanotubes are still fairly new to scientists in the sense that some of their properties, as well as their potential hazards, are not known.
    a. Some people believe that when new materials, such as buckyballs and nanotubes, are advanced through technology, we should utilize them to their fullest potential for the maximum benefit to all. What is your opinion?

    b. What kinds of concerns might some people have regarding new materials like these?

3. Despite their size, nanotubes have been shown to be as much as 200 times stronger than steel. Their electrical conductivity also varies with the three configurations, from conductor, semi-conductor, to non-conductor. Based on these properties, what do you think might be some possible uses for carbon nanotubes?

4. What do you think is the single most significant feature of buckyballs and nanotubes, compared to the other forms of carbon materials?

5. If you were to select one significant feature, more than any other, that makes the buckyball unique from the other allotropes, what would that one feature be?