Landmark Lesson Plan:
Discovery of Fullerenes

Grades: 9-12
Subject area: Chemistry and Nanotechnology
Based on "The Discovery of Fullerenes," a National Historic Chemical Landmark

The following inquiry-based student activities are designed for use in high school lesson planning. The handout, video and activities will help students understand the chemistry of fullerenes and to appreciate the events that led to their discovery.

The activities are designed as a ready-to-go lesson, easily implemented by a teacher or his/her substitute to supplement a unit of study. In chemistry, the activities relate to measurement, diatomic molecules and allotropes, nanoparticles, the relationship of molecular structure to properties of substances, and scientific discovery through collaboration and serendipity.

All resources are available online at www.acs.org/landmarks/lessonplans.

While these activities are thematically linked, each is designed to stand alone as an accompaniment for the handout and video. Teachers may choose activities based on curricular needs and time considerations.

- Take a few minutes to introduce the lesson with a few conversation starters. Have any of the students heard of buckyballs or nanoparticles? What is the smallest piece of matter in their experience? How does this compare to what they know about the size of a cell or a molecule? Has anyone seen the geodesic dome at the Epcot Center in Florida, or any other geodesic domes?
- Show the video on **Nanotechnology's Big Impact**. (8 min.)
- Have students read the handout on the **Discovery of Fullerenes**.
- Distribute the **Reference Materials** and **Activities** selected for the class.
- After class use the **Answer Guide** for student feedback and discussion.

Student Activities with Objectives

Measurement Activity: The Power of Prefixes! (25-30 min.)
- Students develop familiarity with commonly used measurement prefixes and relate their meanings to word equivalents, decimal equivalents and powers of ten.
- Students explore the relationships of prefix magnitudes and relate their uses to familiar objects.

Sequencing Activity: The Discovery of Fullerenes (20-30 min.)
- Students use the handout to analyze a sequence of events that show how architectural inspiration, scientific collaboration and serendipitous observation all played a role in the discovery of fullerenes.

Elements that Come Together: What Are Molecular Elements? (15-20 min.)
- Students learn the diatomic elements and practice writing their formulas.
- Students explore the concept of allotropes.

An Element of Many Forms: Allotropes of Carbon (15-20 min.)
- Students compare properties of different allotropes of carbon (graphite, diamond and fullerenes) and relate the differences in their properties to their molecular structures.

Building Buckyballs: Model Construction Activity (30-40 min.)
- Students construct a cardstock model of C_{60} and use it to observe and answer questions about its structure. (This activity is suitable for individual or group work.)

The Discovery of Fullerenes

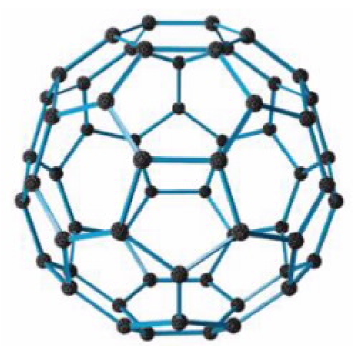
The discovery of new, all-carbon molecules known as fullerenes was the unexpected result of research into particles found in space. Scientists in different fields collaborated on the research that led to this discovery. No one set out to discover fullerenes—they were observed by scientists alert enough to realize they were seeing something new.

Today, fullerenes are at the heart of nanotechnology—the study of extremely small structures and devices on the atomic scale. This field provides many exciting new research possibilities for scientists.

Carbon Chemistry

Carbon, the basis of life, is one of the most common elements and one of the most studied. It comprises the whole discipline of organic chemistry.

A study of pure carbon would not seem all that exciting to most chemists. However, for British chemist Harry Kroto and the colleagues he enlisted in his research, a study into carbon molecules led to the discovery of a previously unknown, all-carbon molecule known today as a fullerene.



This is a Buckminsterfullerene or buckyball, a molecule made up of 60 carbon atoms arranged in the shape of a sphere. Fullerenes can also be shaped like cylinders, known as nanotubes.

Looking Up At the Stars

Harry Kroto, an organic chemist in the University of Sussex in the United Kingdom, became fascinated with various "peculiar" aspects of carbon chemistry. He also was interested in astrochemistry, the makeup of space and celestial bodies in the universe.

Kroto wanted to investigate the origins of the long linear carbon chain molecules he and Canadian scientists had discovered in interstellar space. He hypothesized that these unusual, long, flexible molecules had been created in the atmospheres of carbon-rich red giant stars, and he wanted to test this theory. But carbon, one of the most common elements, was already one of the most studied. At first, it was difficult for Kroto to find support for his research.

Collaboration

At a conference in 1984, Kroto met his friend Robert Curl, an American chemist who was working with colleague Richard Smalley at Rice University in Houston, Texas, to study atom clusters using a special instrument. Called an AP2 ("app-two"), the machine helps scientists study clusters of any element.

Kroto accompanied Curl back to his lab and examined the machine. He saw the possibility of putting carbon in it to explore his theory about carbon chain formation.

But Smalley had his own research to perform and didn't initially offer the AP2. However, a year later, Smalley agreed to let Kroto use the instrument for his experiments. Late in 1985, Kroto arrived in Houston to begin his experiment with Smalley and Curl.

The three scientists, aided by graduate students Sean O'Brien, James Heath and Yuan Liu, conducted the study. The students ran the AP2 with Kroto directing the experiments.

Within days, two significant results emerged from the experiments: First, the team found the long carbon chains in Kroto's hypothesis. Second, the scientists observed a previously unknown molecule of pure carbon.

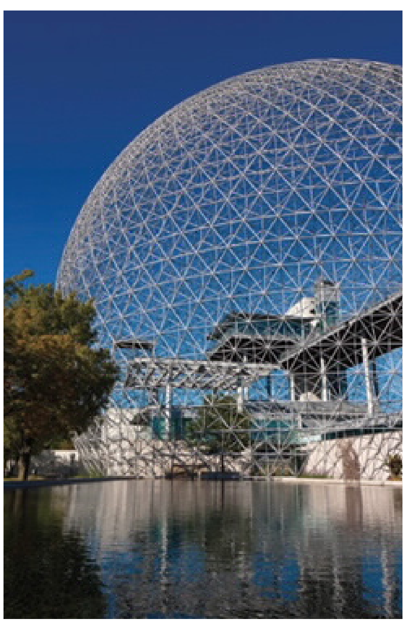
Unexpected Results

Using a mass spectrometer (a device used to determine the mass and molecular composition of molecules), the students noticed something remarkable: an odd indication of a molecule containing sixty carbon molecules. The molecule, C_{60}, formed very readily and exhibited extraordinary stability.

All known carbon-containing molecules, even benzene, a very stable ring of carbon atoms, have edges that terminate with other elements. But C_{60} was inert—it did not need hydrogen, or any other element, to tie up its bonds.

The scientists were stumped at first by the stable, 60-carbon molecule that did not react with other molecules, which suggested it had no dangling bonds: What was the structure of this new form of carbon?

The team considered two candidates for the structure of C_{60}: a flatlander model where carbon was stacked in hexagonal sheets, with the dangling bonds tied up in some fashion; or a spherical form where the hexagonal graphite sheet curled around and closed. A spherical structure would have no dangling bonds.



Buckminster Fuller's Montreal Biosphère at the 1967 World Exposition in Montreal.

At some point Buckminster Fuller, an American architect known for designing spherical structures called geodesic domes, was mentioned. Kroto recalled Fuller's architecture from a visit to the 1967 World Exposition in Montreal.

Kroto and Smalley thought hexagons made up the surface of Fuller's structures. Then Kroto remembered a dome he once made for his children. He thought it had both pentagonal and hexagonal faces, but he was unsure.

Eureka!

Smalley wondered if a shape composed of only hexagons could close. Perhaps the only way to find out was to build one.

Smalley tried first to generate the structure on his computer. Then he turned to paper, tape and scissors.

He began by cutting out and taping together hexagons, but when he attached them, he found that the hexagons would not close. Then he remembered Kroto's suggestion and began adding pentagons to the model.

Now no cheating was required. The model easily assumed the shape of a bowl. By interspersing pentagons among the hexagons, the result was a spherical structure with sixty vertices. Sixty, it turned out, was the only number of atoms that could form a nearly perfect sphere.

When Smalley tossed the paper model on a table in his office the next day, the team was ecstatic. Smalley had stumbled through trial-and-error on a mathematical truth Fuller employed in his domes, and which is exhibited in soccer balls: A spherical shape can be made using 12 pentagons and 20 hexagons.

Nobel Prize

At first, some scientists were skeptical of the team's discovery. With carbon being so well-studied, few imagined that new all-carbon structures would be possible. However, by the late 1980's, further proof of the existence of fullerenes made acceptance widespread.

In 1996, Curl, Kroto and Smalley received the Nobel Prize in Chemistry for their discovery of fullerenes. The presenter of the Nobel noted that the discovery of fullerenes has implications for all the natural sciences.

Nanotechnology

Research on fullerenes has resulted in the synthesis of more than a thousand new compounds. The discovery of fullerenes also led to research in carbon nanotubes, the cylindrical cousins of buckyballs. Carbon nanotubes can slide within an outer tube, suggesting possible uses in tiny motors and as ball bearings and lubricants.

Today, researchers are exploring nanotechnology in a search for applications in such areas as energy, body armor, antibiotics, superconductors, and optics.

More than 25 years after their discovery, fullerenes provide abundant research opportunities in pure chemistry, materials science, pharmaceutical chemistry and nanotechnology.

Discovery of Fullerenes: Reference Materials

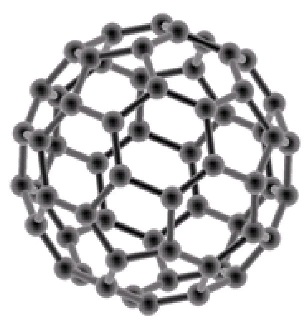
Table of Prefixes

Prefix	Symbol	Power of Ten	Decimal Equivalent	Word Equivalent
kilo	(k)	10^{3}	1000	one thousand
deci	(d)	10^{-1}	0.1	one tenth
centi	(c)	10^{-2}	0.01	one hundredth
milli	(m)	10^{-3}	0.001	one thousandth
micro	(µ)	10^{-6}	0.000001	one millionth
nano	(n)	10^{-9}	0.000000001	one billionth

Prefixes are added to the beginning of the unit of measurement (grams, seconds, meters, etc.) as in **millimeter**, which means **one thousandth of a meter**.

Symbols for prefixes are used in front of base measurements, as in the symbol for millimeter (**mm**).

This soccer ball measures **65 centimeters** (**cm**) around.



The distance around a buckyball is about **3.45 nanometers** (**nm**), or **3.45 billionths of a meter** around.

The circumference of the geodesic dome at the Epcot theme park in Disney World is **0.22 kilometers (km)**.

Student Name: ____ Date: _______________ Period: ______

Measurement Activity: The Power of Prefixes!

To become comfortable using prefixes in measurement, we need to be able to recognize their symbols and their meanings, and express them using words and mathematical terms.

Directions:

1. Use the reference sheet on prefixes to complete the following table.

Prefix	Meaning in Words	Prefix Symbol
kilo		
deci		
centi		
milli		
micro		
nano		

2. Express the powers of ten in the first column in decimal form, as words and as prefix symbols.

Power of ten	Decimal Form	Meaning in words	Prefix symbol
1×10^{-3}			
1×10^{3}			
1×10^{-1}			
1×10^{-2}			
1×10^{-9}			
1×10^{-6}			

3. Find two pairs of **prefixes** that differ from each other by a factor of 10:

   ____________________ and ____________________

   ____________________ and ____________________

4. Find two pairs of **prefixes** that differ from each other by a factor of 1000:

   ____________________ and ____________________

   ____________________ and ____________________

5. Express the following quantities using **prefixes and powers of ten**.

Example: 4 millionths of a gram   4 µg 4×10^{-6} g

a. 9 billionths of a second   ____________   ____________

b. 124 thousand grams   ____________   ____________

c. 6 thousandths of a second   ____________   ____________

d. 5 hundredths of a meter   ____________   ____________

e. 75 tenths of a gram   ____________   ____________

6. Express the following quantities using: **words**   **prefixes**

Example: 6.3×10^{-1} g   6.3 tenths of a gram   6.3 dg

a. 4.9×10^{3} g   ____   ________

b. 5.7×10^{-3} g   ____   ________

c. 9.8×10^{-9} g   ____   ________

b. 5.7×10^{-6} g   ____   ________

7. Use **prefix symbols** and **base measurement symbols** to complete the following:

Example: The length of a mile is 1.6 thousand meters or __(1.6 km)__.

a. The length of a protein molecule is 5 billionths of a meter or __________________.

b. The length of an ant is 5 thousandths of a meter or __________________.

c. The height of a basketball player is 2 meters or __________________.

8. When working with prefix quantities, it is also useful to review what we know about places names in the decimal system. For example, given the measurement **3,168.049725 g**:

a. What number is in the thousands place? ______

b. What number is in the tens place? ______

c. In the tenths place? ______

d. In the hundreds place? ______

e. In the hundredths place? ______

f. In the thousandths place? ______

g. In the millionths place? ______

h. Express the number above in kilograms using the correct prefix and symbol.

____

i. Now try expressing 125 µg in decimal form.: _______________________________

Student Name: ____ Date: _______________ Period: ______

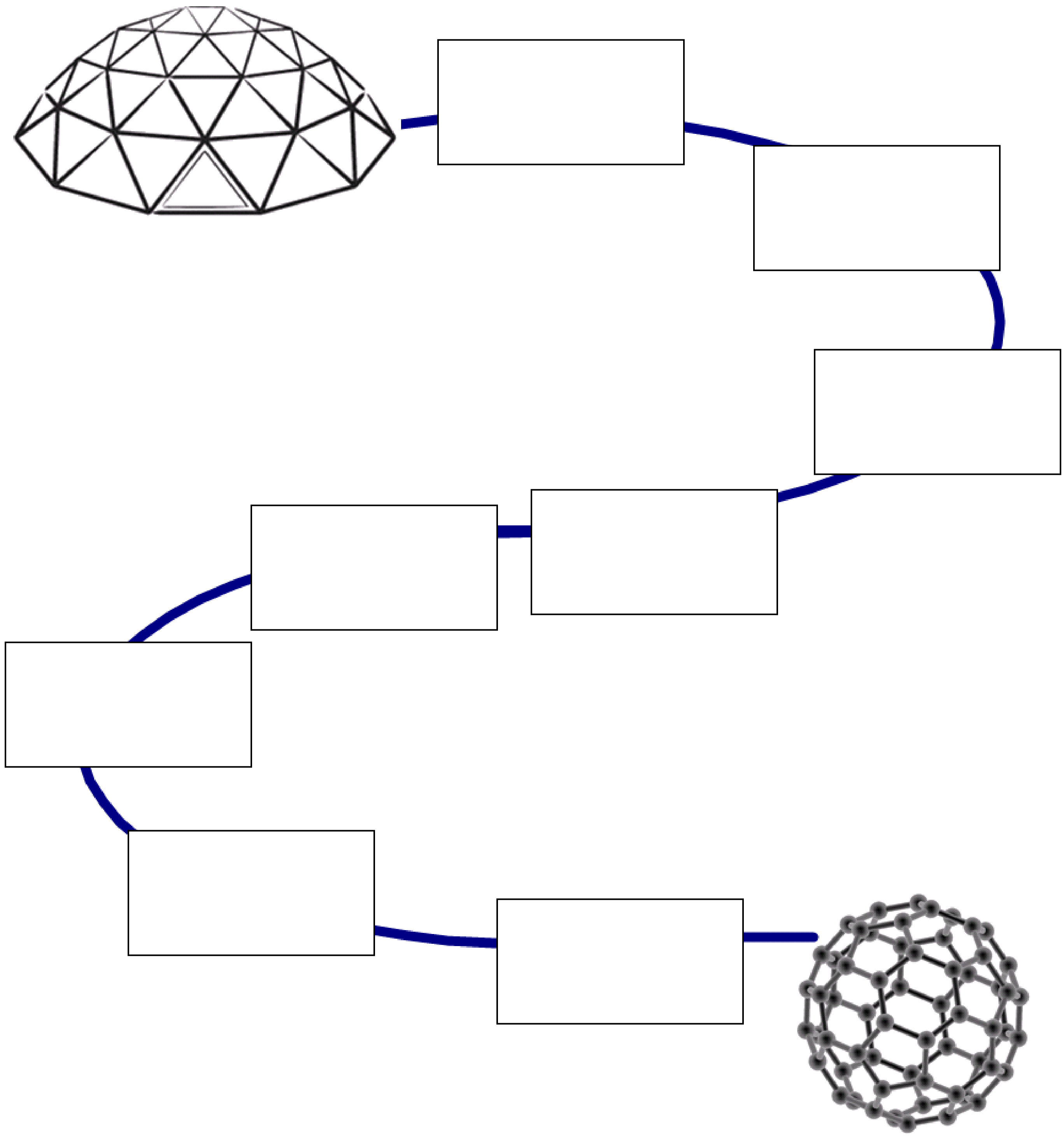
Sequencing Activity: The Discovery of Fullerenes

The discovery of fullerenes was not the work of a single genius; rather it came about through the collaborations and work of many people in different fields. No one set out to discover fullerenes. They were "happened upon" by scientists alert enough to realize they were seeing something new.

Directions:

Read the handout that tells the story of the discovery of fullerenes. Then, cut out the boxes below and glue or tape each box on the timeline on the following page to show the order in which they occurred.

The scientists notice an odd mass spectrometer result.
Smalley agrees to have Kroto use the AP2 instrument.
Curl meets Kroto at a conference and tells him about AP2.
Geodesic dome displayed in Montreal at Expo '67.
Kroto becomes curious about carbon chains in space.
New science of nanotechnology begins.
C_{60} is shown to be a stable molecule.
Smalley builds a buckyball model to describe C_{60}.



Student Name: ____ Date: _______________ Period: ______

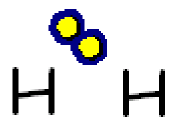
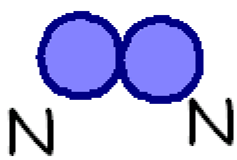
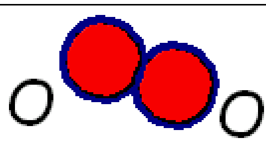
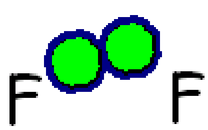
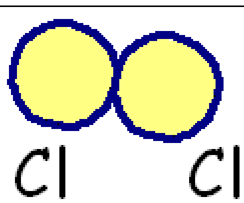
Elements that Come Together: What Are Molecular Elements?

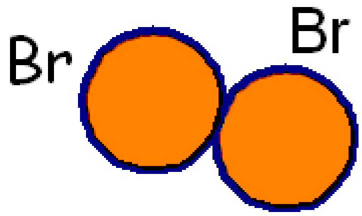
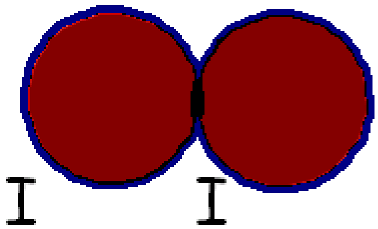
We have learned that the smallest particle of an element that shows all of its chemical properties is called an atom. Some elements, however, do not appear in nature as single atoms. Whenever in their pure, or elemental, state, their atoms always form molecules, bonded together in sets of two, four, eight or more. Buckyballs, for example, are pure structures of carbon, molecules with 60 carbon atoms bonded to each other. Most molecular elements, however, are diatomic, that is, they come as a pair. It is important to always represent them in this way when we write their formulas in chemical equations.

Practice #1: Identifying Molecular Elements

<u>Directions:</u>

The molecules of these important elements are represented below. Fill in the chart with their names and with the symbol used to represent them.

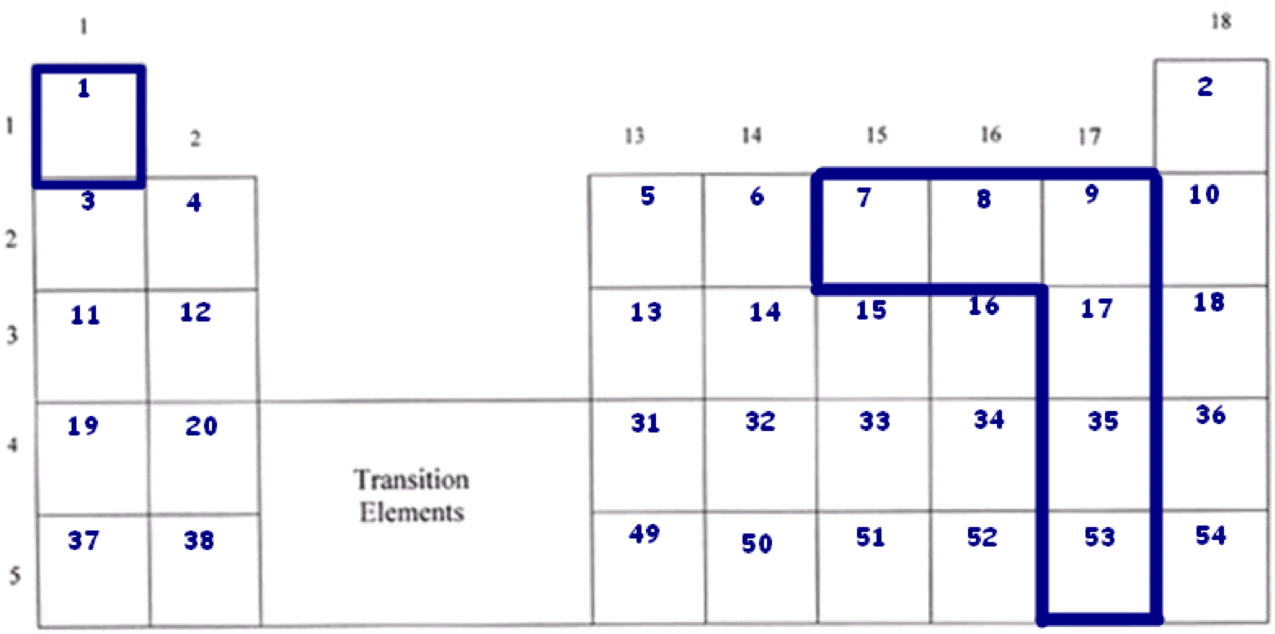
The Diatomic Elements		
Molecule	**Symbol**	**Name of the element**
	H_2	Hydrogen
		
		
		
		

These seven elements are important to learn, and one easy way to remember them is to look at their positions on the periodic table. They form a convenient pattern to remember!

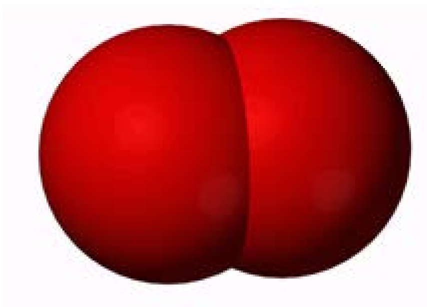
There are **seven** diatomic elements, so start with atomic number **7**. Then trace a **seven** on the table - these elements are diatomic. There is **one** left over, and you will find it at atomic number **1**!

Put the symbols for the diatomic elements in their squares in the periodic table below.



Practice #2: Allotropes of Elements

Some molecular elements have more than one molecular structure, and these are known as **allotropes** of the element. Represented below are two allotropes of oxygen:

O_2 Diatomic Oxygen	O_3 Ozone
	

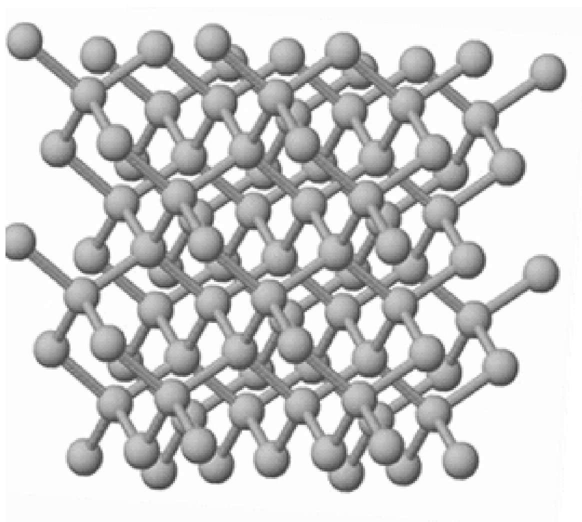
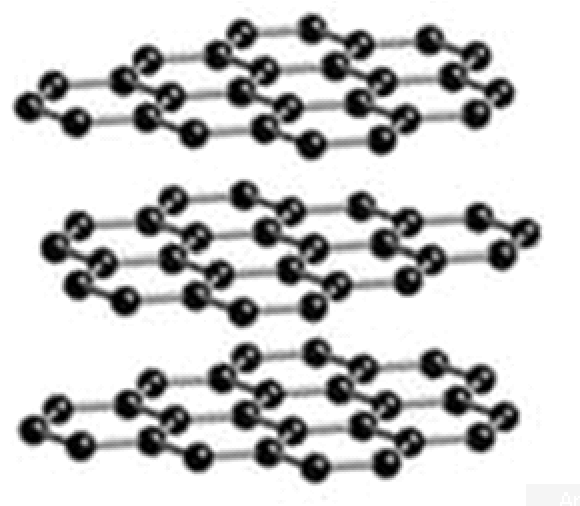
Diatomic oxygen is the oxygen gas we are familiar with, that we need to breathe, and that reacts with carbon based fuels to produce carbon dioxide and water. Ozone is a toxic, reactive gas, damaging to biological life when it forms near the earth's surface, but we couldn't survive on Earth without the protective layer of ozone gas that forms in the stratospheric layer of our atmosphere. High above the earth, ozone's high energy bonds absorb UV light from the sun, preventing 97-99% of these light rays from reaching the earth's surface.

The element sulfur forms more than 30 solid allotropes, with bright yellow S_8 being the most common. Experiment in the space below with drawing all the different ways that you can think of that eight atoms of sulfur could combine to form a molecule:

Student Name: ______________________________________ Date: ______________ Period: ______

An Element of Many Forms: Allotropes of Carbon

1. The graphite in a pencil and the diamond in a ring are both composed of pure carbon. Two forms of the same element are known as allotropes of the element. Their properties are very different!

Diamond	**Graphite**
	
How many other atoms is each carbon atom bonded to? __________	How many other atoms is each carbon atom bonded to? __________

2. Draw an arrow from each box to the structure that you think would best explain the physical properties of graphite and diamond described below:

A silvery, soft, black solid

Leaves a streak when drawn across a piece of paper

Will not conduct electricity (an electrical insulator)

Diamond

An electrical conductor

An excellent lubricant (helps surfaces slide easily across each other)

Graphite

The hardest natural substance known

A transparent solid

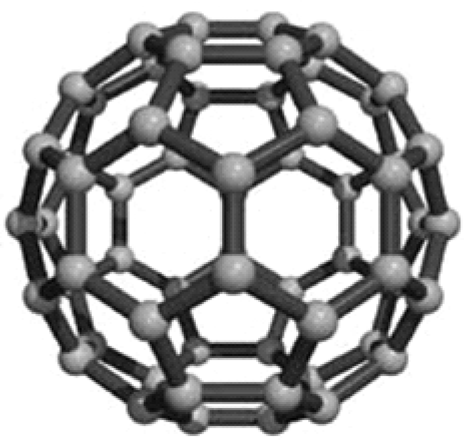
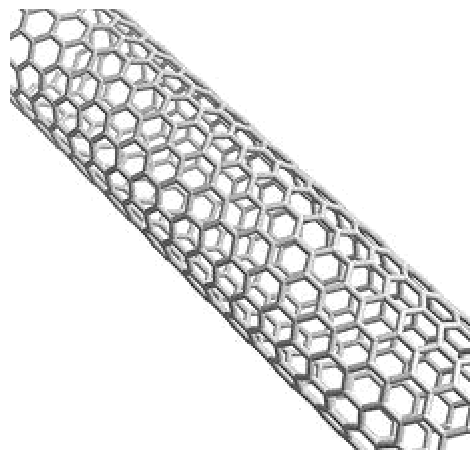
Used to make cutting and grinding tools

3. Now read the two statements below and choose between the two allotropes to fill in the blanks!

In _____________, every carbon atom forms a strong covalent bond to four other carbon atoms, which in turn are bonded to four atoms of carbon. This structure can continue indefinitely. Since all of carbon's four bonding electrons are "tied up" in strong covalent bonds, there are no electrons that are free to move through the crystal, which explains why ______________ is an electrical insulator (does not conduct electricity). And since every atom is strongly bonded to four others, it is very difficult to tear atoms out of the crystal, which explains why ______________ is such a hard substance.

In _______________ each carbon atom is strongly bonded to only three other carbon atoms, which in turn are strongly bonded to a total of three carbon atoms, etc. This forms what basically are flat two-dimensional planes of carbon atoms. These planes are arranged parallel to each other, like a stack of papers. The fourth electron is highly delocalized (can move freely) across many atoms, which makes it easier to conduct electricity. Since there is no significant bonding between the planes of carbon atoms, they can easily slide over each other and be removed, which explains why ________________is soft and can be used in pencils.

4. Buckyballs and nanotubes are also allotropes of carbon:

Buckyball	**Nanotube (one of many variations)**
 How many other atoms is each carbon atom bonded to? __________	 How many other atoms is each carbon atom bonded to? __________

5. Based on these structures do you think these particles would have properties similar to diamond or similar to graphite? Why?

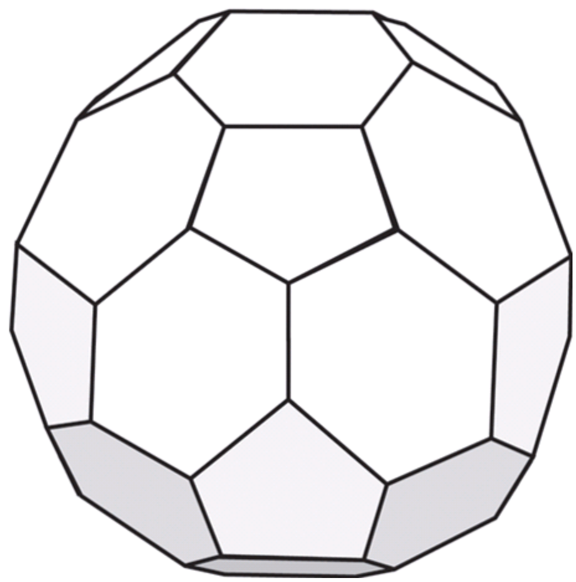
6. What aspect(s) of the nanotube structure explains why there is interest in developing them as tiny electrical components?

Student Name(s): ____

Date: _______________ Period: ______

Building Buckyballs: Model Construction Activity

Building a buckyball can give us some great insights into the truncated icosahedron structure of a C_{60} molecule. As we handle the model we will be able to examine the relationships between the geometric shapes that compose this form.



The structure is composed of

12 pentagons (representing 12 rings of carbon atoms with 5 atoms in each ring)

20 hexagons (representing 20 rings of carbon atoms with 6 atoms in each ring)

Materials to gather before starting:

Sheets of card stock paper

Scissors

Pencils

Transparent tape

The pentagons and hexagons can be cut from different colored paper to highlight the pattern of the final structure.

Once you have put together your model, work with others in your group to answer the questions below:

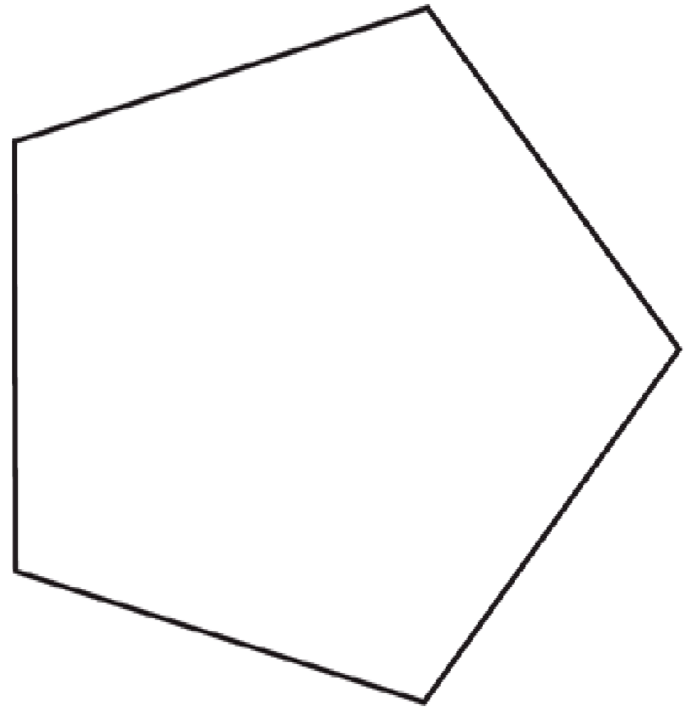
1. Are the 5-membered rings of carbon isolated or contiguous? (That is, are they separate from the other pentagons or connected to them?) ______________________________
2. Are the 6-membered rings of carbon isolated or contiguous? ______________________
3. How many faces does the structure have? ______________________
4. How many other carbon atoms does each carbon atom connect to? ___________________
5. Use a protractor to measure the angles of the edges at each carbon atom:
   ____
6. How many edges are there where two pieces touch in your model? ___________________
7. How many edges are there where two hexagons touch? ____________________
8. Look at the hexagons and pentagons and see how they could each be further divided into triangles, like slices of a pizza. If the whole structure were constructed in this way, with triangles, how many triangles would it take? ___________________
9. The hexagonal part of the buckyball structure is like the hexagonal flat structure of graphite. Examine your model to see how the pentagons allow the structure to form a ball, rather than a flat sheet, or a tube. Which do you think places more stress on the carbon atoms, the flat sheet structure of graphite, or the buckyball structure?
   ____
   ____
   ____

Challenge Question:

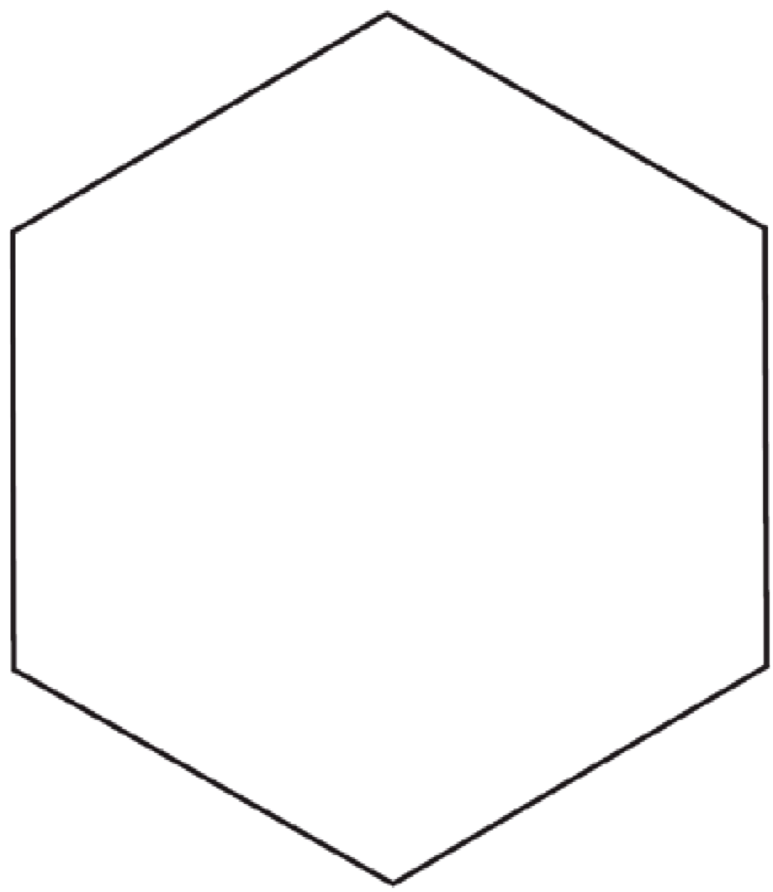
If there are 60 carbons in the buckyball molecule, what is its molar mass? ______________________

Step #1

Cut 12
pentagons

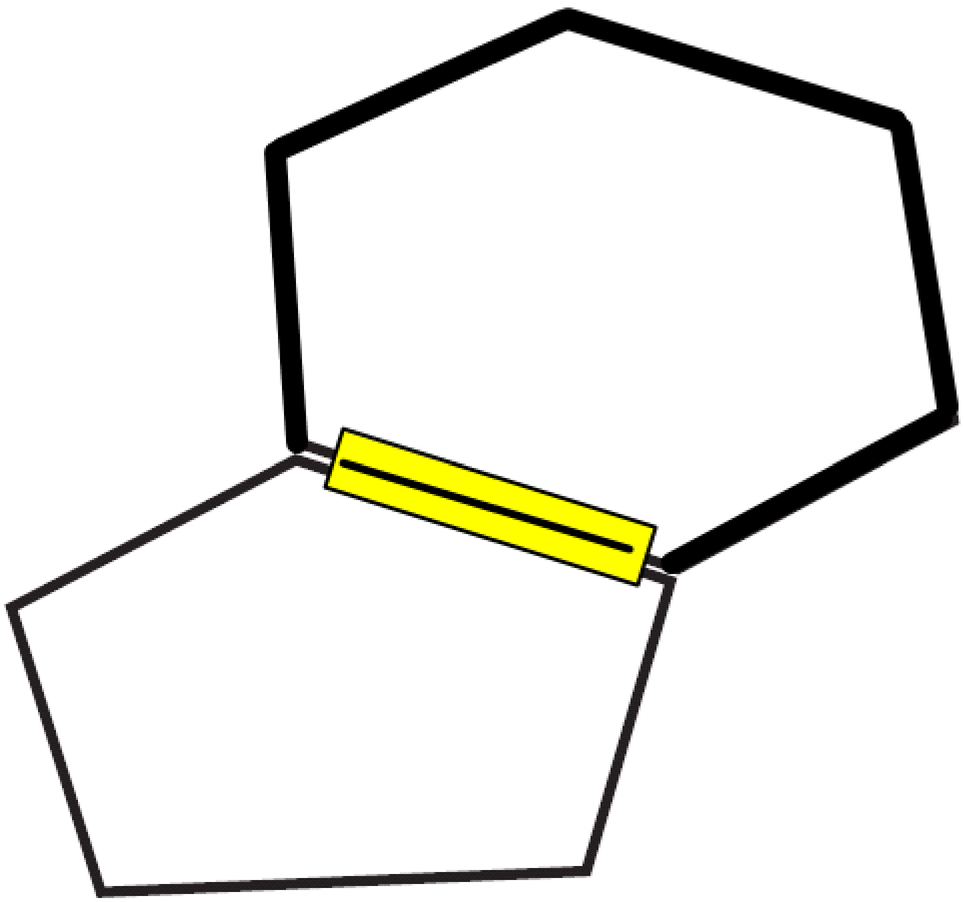


Cut 20
hexagons



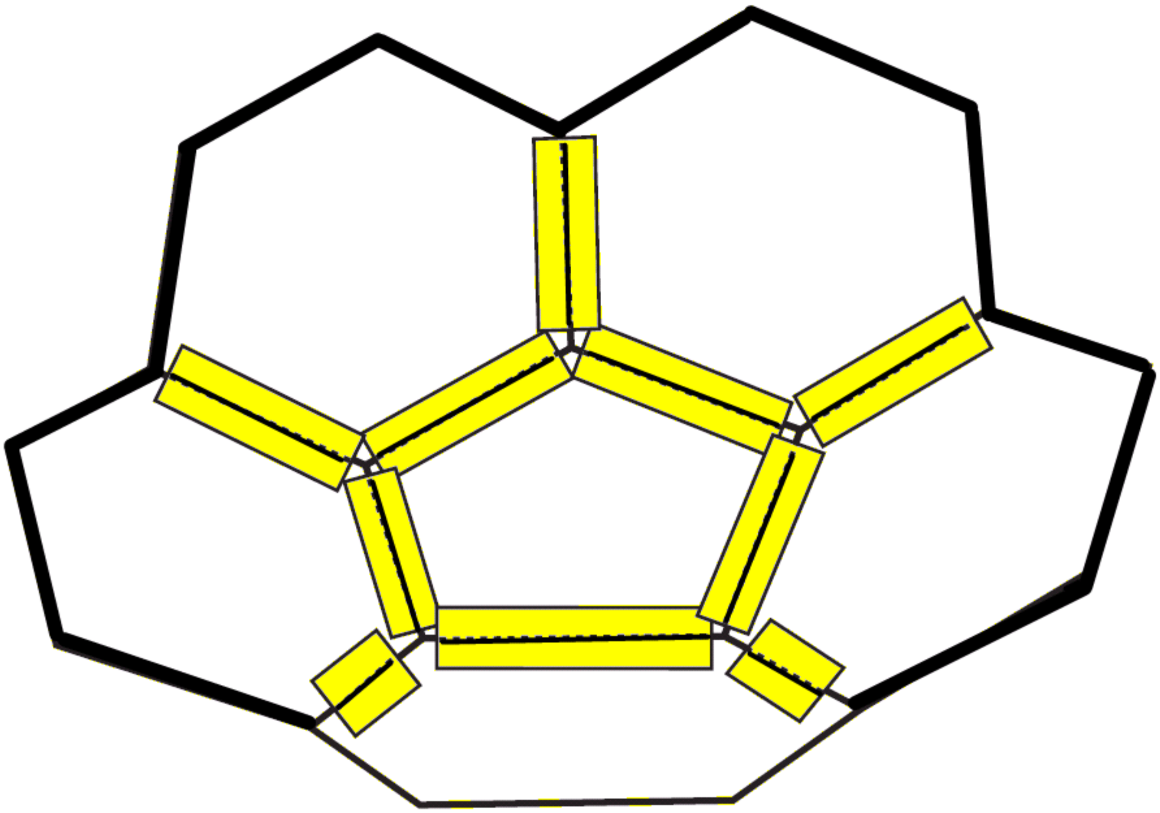
Step #2

Place a hexagon with a pentagon and tape the sides together as below.



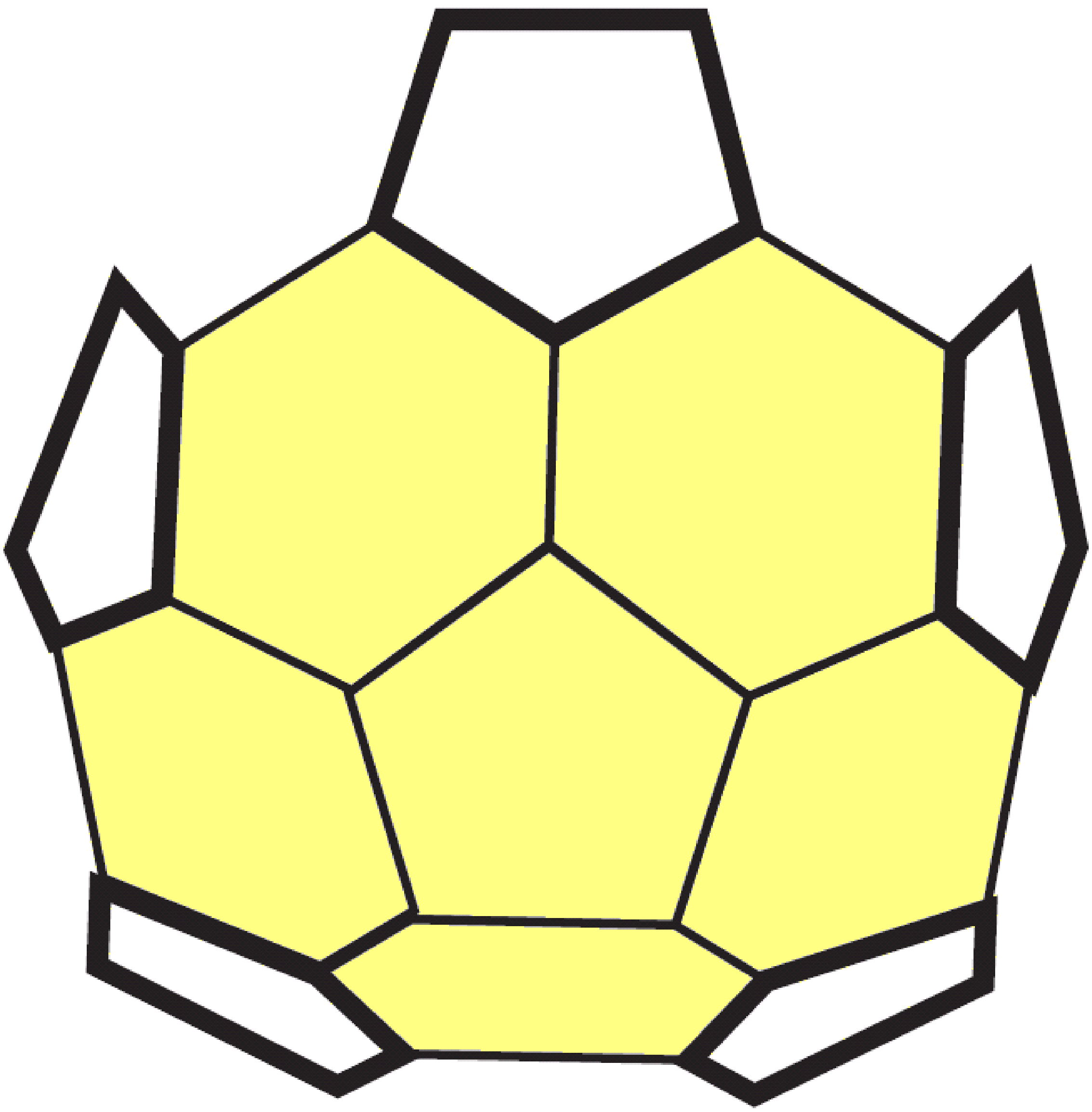
Step #3

Now surround the pentagon with four more hexagons and tape them as shown.



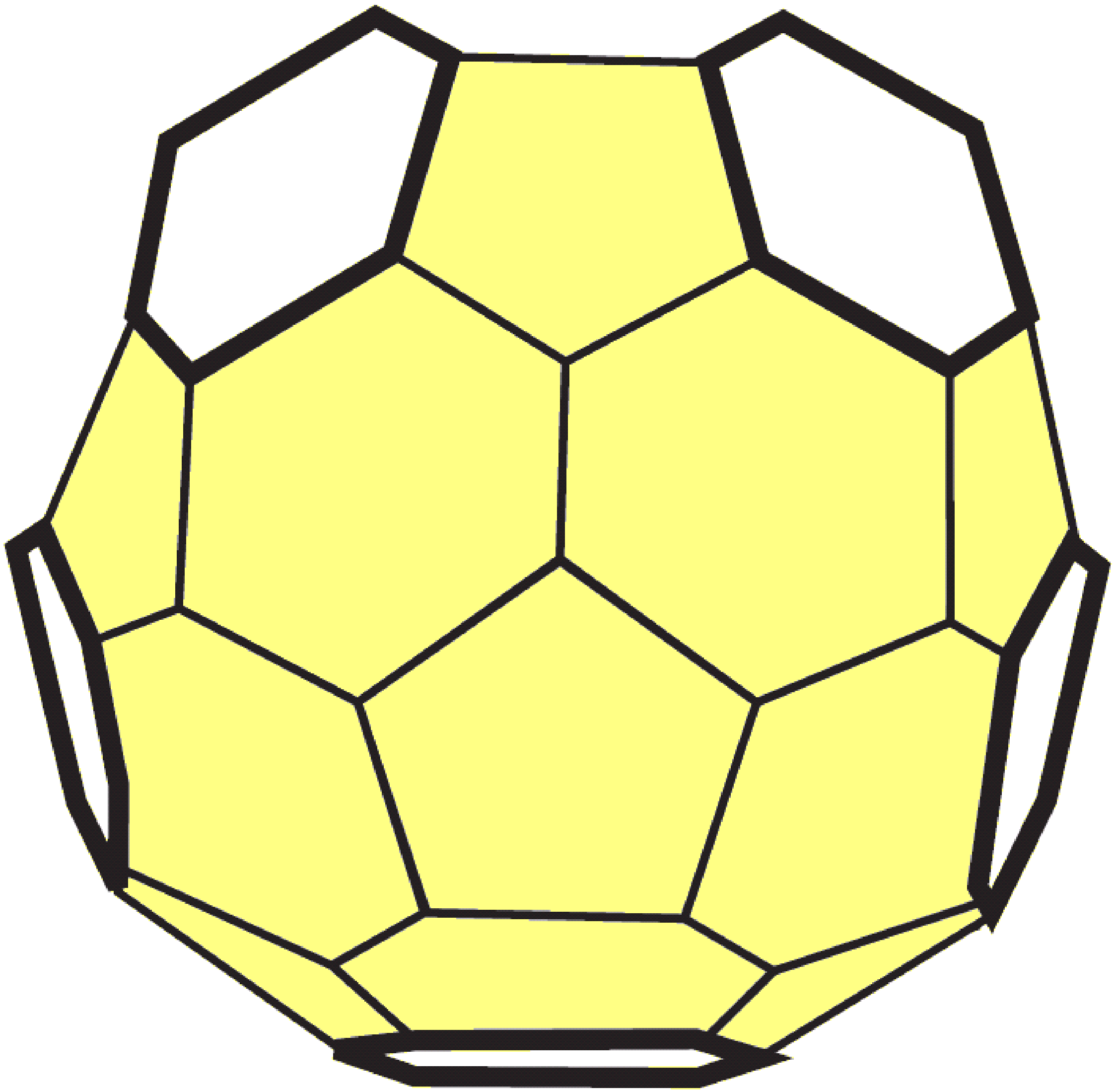
Step #4

Now add five pentagons with tape where the edges intersect, taking care to line up and tape the edges from end to end.

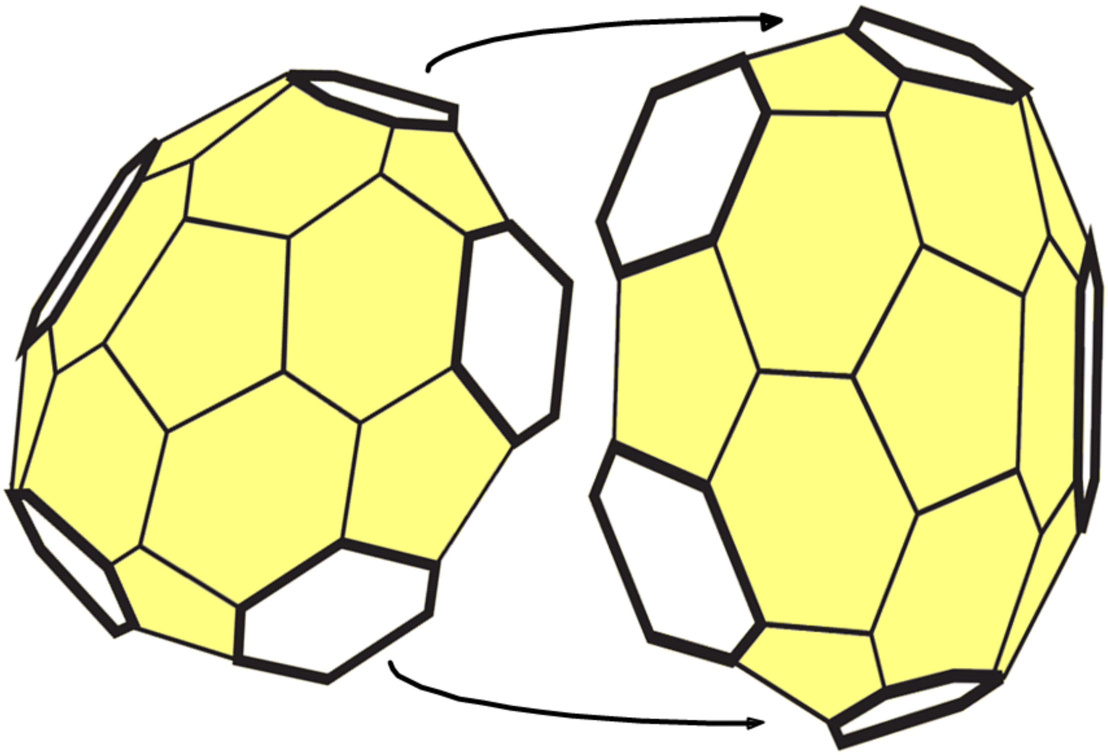


Step #5

Fill in the layer with five more hexagons, and the structure is half finished, with 6 pentagons and 10 hexagons.



Repeat the Steps 1-5, to make another half, and when both are complete, fit them together as below:



Discovery of Fullerenes Answer Guide
Measurement Activity: The Power of Prefixes!

1. Use the reference sheet on prefixes to complete the following table:

Prefix	Meaning in words	Prefix symbol
kilo	**a thousand times**	**k**
deci	**a tenth of**	**d**
centi	**a hundredth of**	**c**
milli	**a thousandth of**	**m**
micro	**a millionth of**	**µ**
nano	**a billionth of**	**n**

2. Express the powers of ten in the first column as words and as prefix symbols:

Power of ten	Decimal Form	Meaning in words	Prefix symbol
1×10^{-3}	**0.001**	**one thousandth**	**m**
1×10^{3}	**1000**	**one thousand**	**k**
1×10^{-1}	**0.1**	**one tenth**	**d**
1×10^{-2}	**0.01**	**one hundredth**	**c**
1×10^{-9}	**0.000000001**	**one billionth**	**n**
1×10^{-6}	**0.000001**	**one millionth**	**µ**

3. Find two pairs of prefixes that differ from each other by a factor of 10:

   deci and centi

   centi and milli

4. Find two pairs of prefixes that differ from each other by a factor of 1000:

   milli and micro

   micro and nano

5. Express the following quantities using prefixes and powers of ten.

   a. 9 billionths of a second — **9 ns** — **9×10^{-9} s**

   b. 124 thousand grams — **124 kg** — **124×10^{3} g**
   (Or, if scientific notation has been introduced, 1.24×10^{5} g.)

   c. 6 thousandths of a second — **6 ms** — **6×10^{-3} s**

   d. 5 hundredths of a meter — **5 cm** — **5×10^{-2} m**

   e. 75 tenths of a gram — **75 dg** — **75×10^{-1} g**
   (Some students may recognize this as 7.5 g.)

Discovery of Fullerenes Answer Guide
Measurement Activity: The Power of Prefixes! (continued)

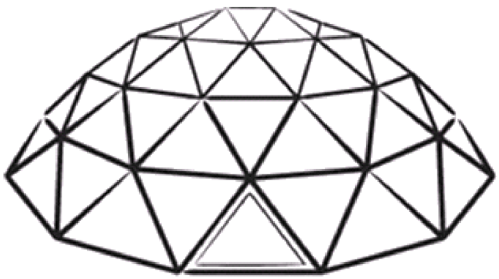
6. Express the following quantities using **words** and **prefixes**

	words	prefixes
a. 4.9×10^{3} g	**4.9 thousand grams**	**4.9 kg**
b. 5.7×10^{-3} g	**5.7 thousandth of a gram**	**5.7 mg**
c. 9.8×10^{-9} g	**9.8 billionth of a gram**	**9.8 ng**
b. 5.2×10^{-6} g	**5.2 millionth of a gram**	**5.2 µg**

7. Use **prefix symbols** and **base measurement symbols** to complete the following:
   a. The length of a protein molecule is 5 billionths of a meter or **5 nm.**
   b. The length of an ant is 5 thousandths of a meter or **5 mm.**
   c. The height of a basketball player is 2 meters or **2 m.**

8. When working with prefix quantities, it is also useful to review what we know about places names in the decimal system. For example, given the measurement **3,168.049725 g**:
   a. What number is in the thousands place? **3**
   b. What number is in the tens place? **6**
   c. In the tenths place? **0**
   d. In the hundreds place? **1**
   e. In the hundredths place? **4**
   f. In the thousandths place? **9**
   g. In the millionths place? **5**
   h. Express the number above in kilograms using the correct prefix and symbol. 3.168049725 kg
   i. Now try expressing 125 µg in decimal form: **0.000125 g**.

Discovery of Fullerenes Answer Guide
Sequencing Activity: The Discovery of Fullerenes



Geodesic dome displayed in Montreal at Expo ’67.

Kroto becomes curious about carbon chains in space.

Curl meets Kroto at a conference and tells him about AP2.

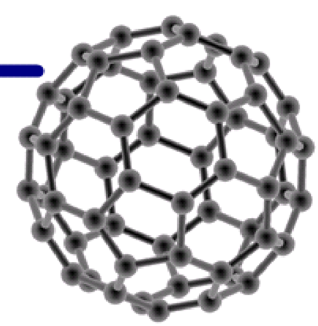
Smalley agrees to have Kroto use the AP2 instrument.

The scientists notice an odd mass spectrometer result.

C_{60} is shown to be a stable molecule.

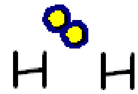
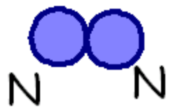
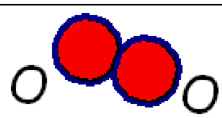
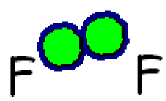
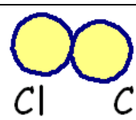
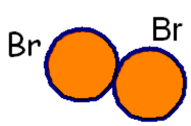
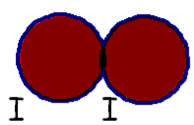
Smalley builds a buckyball model to describe C_{60}.

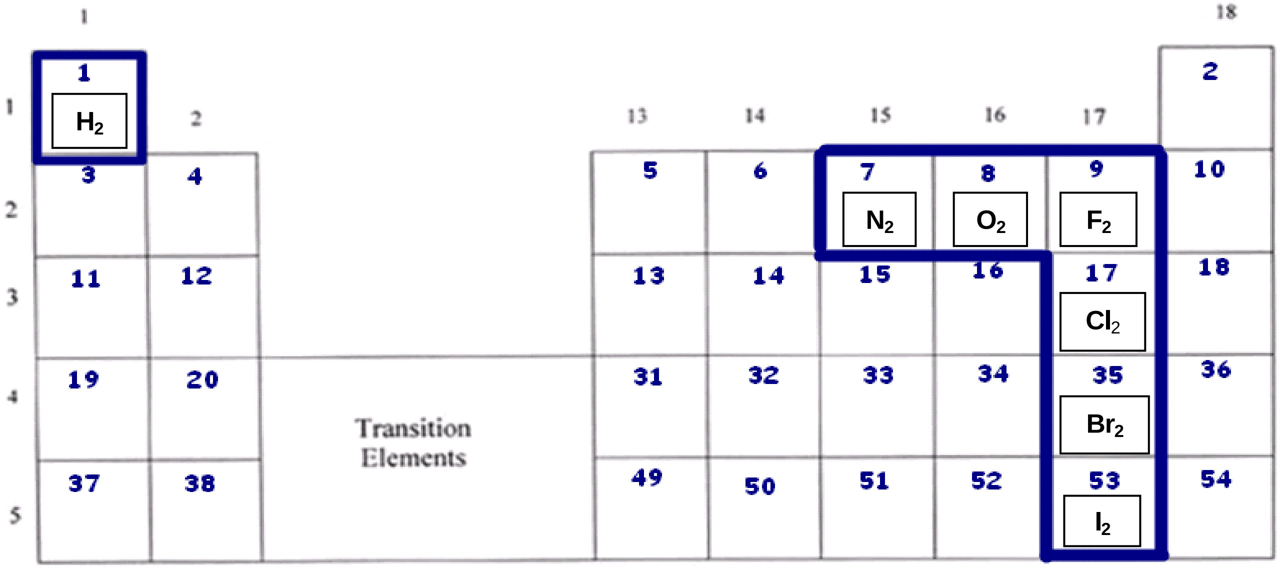
New science of nanotechnology begins.



Discovery of Fullerenes Answer Guide
Elements that Come Together: What are Molecular Elements?

Practice #1: Identifying Molecular Elements

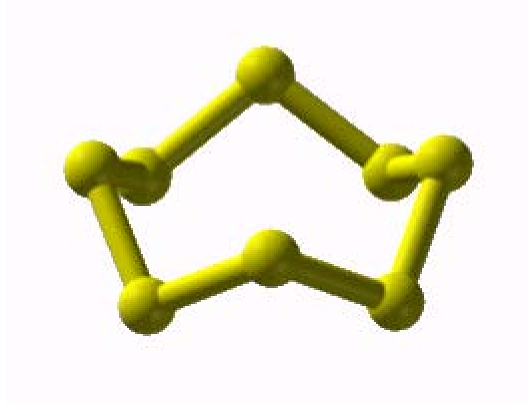
The Diatomic Elements		
Molecule	**Symbol**	**Name of the element**
	H_2	hydrogen
	N_2	nitrogen
	O_2	oxygen
	F_2	fluorine
	Cl_2	chlorine
	Br_2	bromine
	I_2	iodine



Practice #2: Allotropes of Elements

The element sulfur forms more than 30 solid allotropes, with bright yellow S_8 being the most common. Experiment in the space below with drawing all the different ways that you can think of that eight atoms of sulfur could combine to form a molecule:

There are many geometric shapes for students to experiment with that could be formed by eight atoms—linear, T-shaped, diamond shaped, etc. The accepted form of S_8 is a ring as shown below:

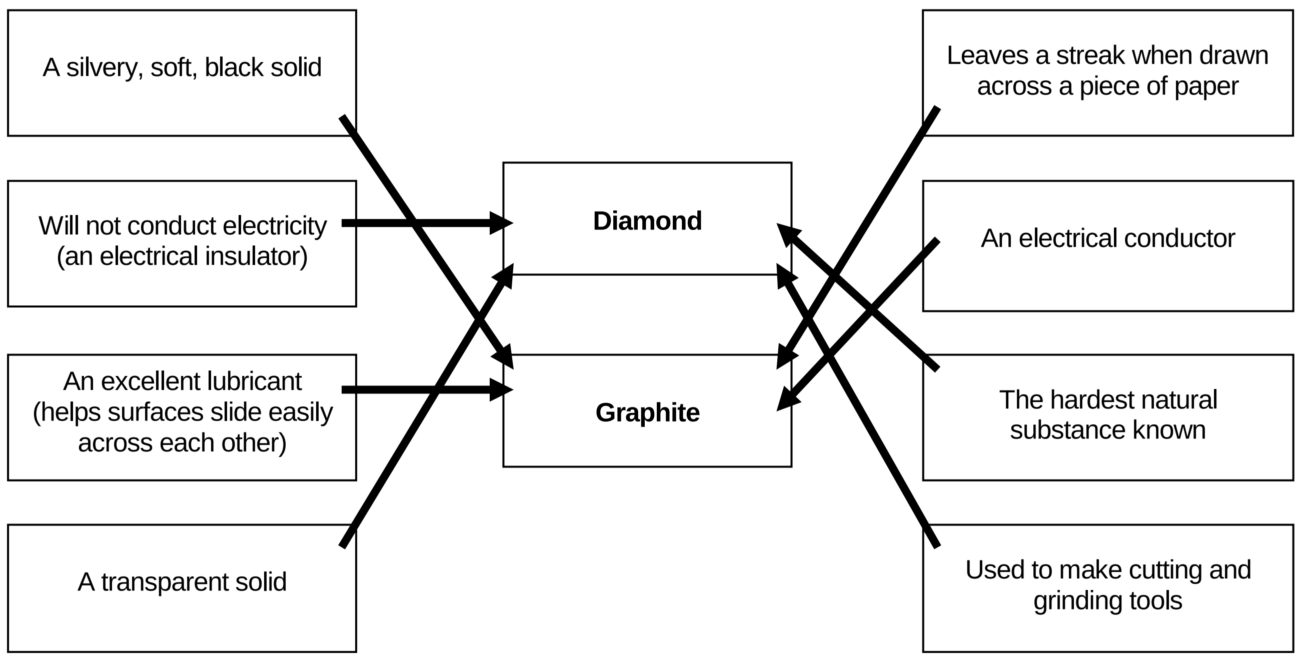


Discovery of Fullerenes Answer Guide
An Element of Many Forms: Allotropes of Carbon

The graphite in a pencil and the diamond in a ring are both composed of pure carbon. Two forms of the same element are known as **allotropes** of the element. Their properties are very different!

1. Each carbon atom in **diamond** is bonded to **4** other atoms.
   Each carbon atom in **graphite** is bonded to **3** other atoms.

2. Draw an arrow from each box to the structure that you think would best explain the physical properties of graphite and diamond described below:



3. Now read the two statements below, and choose between the two allotropes to fill in the blanks!

   The first paragraph refers to diamonds.
   The second paragraph refers to graphite.

4. Buckyballs and nanotubes are also allotropes of carbon. In both buckyballs and nanotubes, each carbon atom bonds to **three** other atoms.

5. Based on these structures (of buckyballs and nanotubes) do you think these particles would have properties similar to diamond or similar to graphite? Why?

   Both buckyballs and nanotubes shown here have carbon atoms attached to 3 other atoms. This is similar to the structure of graphite, therefore their properties would probably be more similar to graphite's properties. One aspect of the geodesic dome built by Buckminster Fuller was its high strength to weight ratio, and buckyballs also may exhibit this trait.

6. What aspect(s) of the nanotube structure explains why there is interest in developing them as tiny electrical components?

   Since each carbon in the nanotube structure is only bonded to three other atoms, one of carbon's four valence electrons on each atom is free to move within the structure. Just as graphite is an electrical conductor due to the freedom some of its electrons have to move within its structure, nanotube particles could be constructed to conduct electricity in a similar way.

Discovery of Fullerenes Answer Guide
Building Buckyballs: Model Construction Activity

1. Are the 5-membered rings of carbon isolated or contiguous? (That is, are they separate from the other pentagons or connected to them?) **The 5-membered rings of carbon are isolated.**
2. Are the 6-membered rings of carbon isolated or contiguous? **The 6-membered rings are contiguous.**
3. How many faces does the structure have? **The structure has 32 faces.**
4. How many carbons is each carbon connected to? **Each carbon is connected to 3 other carbons.**
5. Use a protractor to measure the angles of the edges at each carbon atom:

   The angles at the vertices are the same – all being slightly less than 120 degrees (around 117 degrees), as the structure is not flat.
6. How many edges are there in your model? There are **90 edges in the model.**
7. How many edges are there where two hexagons touch? **There are 30 edges where two hexagons touch.**
8. Look at the hexagons and pentagons and see how they could each be further divided into triangles, like slices of a pizza. If the whole structure were constructed in this way, with triangles, how many triangles would it take?

   (5 triangles for each of 12 pentagons = 60 triangles) plus (6 triangles for each of 20 hexagons = 120 triangles) = Altogether there are 180 triangular pieces.
9. The hexagonal part of the buckyball structure is like the hexagonal flat structure of graphite. Examine your model to see how the pentagons allow the structure to form a ball, rather than a flat sheet, or a tube. Which do you think places more stress on the carbon atoms, the flat

   sheet structure of graphite, or the buckyball structure?

   The buckyball structure forces the flat geometry of the hexagon shapes into a curved, more spherical geometry, and may therefore place more stress on each bond than the graphite or nanotube structure.

Challenge Question:

If there are 60 carbons in the buckyball molecule, what is its molar mass? **The molar mass of a buckyball molecule is 720 g/mol.**